Effect of lime & cement additives on the dynamic modulus of elasticity of a clay soil

Ismail Yolar

EFFECT OF LIME & CEMENT ADDITIVES ON THE DYNAMIC MODULUS OF ELASTICITY OF A CLAY SOIL

by

ISMAIL YOLAR

A

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John B. Heagler Jr.　　J. J. Blanje

John L. Best　　R. F. Davidson

ABSTRACT

This thesis is a study to determine the values and characteristics of modulus of elasticity and the modulus of rupture of a clay soil stabilized with lime and cement in an effort to pave the way for including these values in design criteria.

The modulus of elasticity and the Poisson's ratio were obtained by sonic method. Specimens were broken in flexure for modulus of rupture. Experiments were performed with: (1) untreated soil, (2) soil with 4, 6, 8, and 12 percent cement additive, (3) soil with a 3 percent lime additive and 0, 4, 6, 8, and 12 percent cement additive, (4) soil with a 6 percent lime additive and 0, 4, 6, 8, and 12 percent cement additive, (5) soil with a 9 percent lime additive and 0, 4, 6, 8, and 12 percent cement additive. Effect of cement content, lime content, combined cement and lime content, and length of curing on the strength and elastic properties are shown. Modulus of elasticity of moist-cured specimens ranged from 0.65×10^6 psi. to 2.26×10^6 psi.; modulus of rupture ranged from 32 psi. tp 300 psi.

The strength and modulus of elasticity of all soil-cement-lime mixtures increased with an increase in cement and lime contents and with an increase in moist curing time. Poisson's ratio seemed to be independent of cement and lime contents and age of curing.

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INTRODUCTION

Man has always had the urge to move. Sometimes his motivation has been peaceful, resulting in a search for new and better places and things with which to develop commerce and industry. Sometimes a restless desire for adventure has set men to wandering. At other times his purpose has been armed conquest. But whatever the reasons for human movement the result has been improved transportation modes from the first hard surfaces that appeared in Mesopotamia about 3500 B.C. up to today's modern highways.

Although technological advances have been great during the age of modern highways, and knowledge has been extended in the fields of soils and other highway materials and developments in machinery have revolutionized construction methods, today, the prospect of a continuing increase in the total number of vehicles operating on highways, and the attendant demand for safer, smoother, and more durable thoroughfares still provide a challenge to highway engineers.

A natural earth tract can neither support modern wheel loads nor provide adequate wearing surface, therefore a constructed pavement is required on the top of the soil in order to provide a smooth riding surface, to distribute the traffic loads over the soil formation sufficiently to prevent the soil from being overstressed, and to protect the soil formation from the adverse effects of weather.

The characteristics of the pavement are dependent not only on the nature of the traffic but also on the properties of the subgrade soil on which the pavement is constructed. Unless its supporting power is adequate the surfaces borne by it will not withstand the use for which they are intended. This means that the soil in embankments and cuts must be of a type which will respond to special compaction or other treatment which will produce a durable layer. Such treatment is referred to as subgrade stabilization. The method selected for stabilization of roadbeds is dependent upon local economics of road construction. In many cases, suitable natural material for admixing will not be economically available; therefore other types of stabilizing agents such as cement, lime, asphalt, etc., will have to be considered.

Pavement, either rigid or flexible, when placed directly on subgrade will give good service only when the subgrade conditions are ideal. When conditions are not ideal they may be improved by the addition of base or base and subbase, between the subgrade and the wearing course. The primary function of them is to give uniform distribution of wheel loads over the subgrade by resisting deformation within themselves. Until about 1940 base courses almost always consisted solely of mineral aggregates. Since about 1940 "treated bases" composed of mineral aggregates and additives to make them stronger or more resistant to moisture have become increasingly common. The use of lime in soil stabilization is rapidly gaining acceptance. It is noteworthy that the use of soil-cement mixture, from its early infancy in South Carolina to its present world-wide use, was guided and supervised scientifically and precise records have been kept on its development.

Methods for determining thickness requirements for flexible pavement have been in development for many years. Early formulae assumed point loading at the surface and uniform distribution of load at 45 degrees downward in the shape of an isosceles pyramid. This results in a loaded area on the subgrade which is square and has side dimensions of twice the pavement thickness. It was next suggested that, instead of square area of distribution on the subgrade, that area be considered to have two straight and two arced sides. This was later evolved into a circular area on the subgrade over which load was assumed to be uniformly distributed. After low pressure tires came into use it was recognized that the load was distributed over a considerable area at the surface, not at a point. This resulted in the concept of load distributed through a conic frustum. To overcome the difficulty of analysing the true stress-strain characteristics of the soil and the true distribution of stress in the layers undera wheel load, methods mentioned above make certain assumptions and neglect some factors. If we consider these design methods for flexible pavements in one group, we can say that this group contains methods using a simplified theory of stress distribution and soil strength, supported by the justification of experience. There are also methods for flexible pavement design which differ from other methods in their reliability and in their method of approach to the problem. We can classify these design methods in two groups: Group (1), empirical methods using soil classification tests for comparing with past experience of the thickness of construction required, such as Group Index Method; Group (2), empirical methods using a special soil strength test for comparing with past experience, such as C.B.R. Method. The use of flexible pavement for airports where wheel loads much greater than those operating on highways must be considered, has further increased the need for design method which with accuratly determine optimum thickness requirements. In general, we can say that developments have brought two important items into consideration:

(1) The manner in which stress is distributed from the surface downward.

(2) The relative ability of subgrade to support the design load transmitted to it with deflections not to exceed 0.10 to 0.35 inches.

The development of methods for the design of the thickness of rigid pavements has been largely separate from that of flexible pavements. In the design of the thickness of concrete pavements originating with Westergaard's analysis, consideration has been mainly given to the stresses within the concrete, and subgrade has only been considered in so far as it affects these stresses.

The modulus of elasticity and Poisson's ratio play an important role in the dimensional design of homogeneous pavements. Questions regarding the strength of a pavement, its reaction to temperature and moisture changes, and the distance and type of joint to be used are directly related to the elasticity constants. These constants must be determined for soil-lime or soil-cement in order to understand its actual behavior under stresses caused by external applied loads. From a knowledge of their magnitudes, a better utilization of these properties of this new construction material may result as well as an expansion of its field application.

The test results of this thesis point out the fact that the particular soil stabilized with lime and cement appears to have flexural rigidity which is not considered in flexural pavement design. This thesis is an attempt to determine the values of modulus of elasticity and rupture of a clay soil stabilized with lime and cement in an effort to pave the way for including these values in design criteria.

REVIEW OF LITERATURE

The use of lime in road construction dates back to the early Romans who are considered the first road builders of consequence. The base of the famous Appian way was made up of layers of broken stone, broken bricks, lime and broken pottery, well compacted and covered with a layer of large, carefully fitted paving stones.

Very little work has been done on the modulus of elasticity and flexural rigidity of stabilized soils. However, a tremendous volume of research and investigation have been reported concerning the strength and durability characteristics of soil-lime and soil-cement. Since these factors influence the use of stabilized soil as base material some of the most important reports are reviewed herein.

The earliest experiments in the United States using hydrated lime as a stabilizing material were performed by the University of Missouri, in cooperation with the National Lime Association in 1923 (1). They treated 500 ft. of clay road with hydrated lime near Hallsville, Missouri. The aim of the research was to determine the feasibility of treating clay soils with hydrated lime to prevent them from sticking to the wheels of the moving vehicles, thus allowing travel on soil roads during the wet seasons of the year. The result was reported "the clay and lime mixture does not stick on the wheels of passing vehicles but smooths out and packs much more quickly than does the untreated clay". This was the first report indicating the possibility of using lime as a stabilizing agent.

The results of the laboratory research conducted by the Engineering Experiment Station of Purdue University, sponsored by the National Lime Association, was reported by Mr. A. M. Johnson (2) during the twenty-eighth annual meeting of the Highway Research Board in 1948.

The experiments were organized in three broad parts on the basis of soil types used. In part one Atterberg Limit tests were run on 25 different fine-grained soils by addition of 0, 2, and 5 percent of hydrated lime.

Compaction tests were made on 11 of the 25 different fine-grained soils with 0, 2, and 5 percent of lime, using standard Proctor procedure. The addition of lime was accompanied by decreases in maximum density and increases in optimum moisture content. From penetration test, it was found that the addition of lime increased the resistance to penetration.

Tests in part two were performed on 5 natural gravels. Optimum moisture content of these soils were determined using a modified procedure and CBR molds. CBR specimens were molded at or near optimum moisture content with 0, 2, and 5 percent of lime. CBR tests were made on each combination of soil and lime, following three different methods of curing: (1) as molded;

(2) after 7 days of capillary saturation; and (3) after drying to constant weight at 140°F and then subjecting to 7 days saturation. In most cases, the period of drying before wetting added to the strength at the time of testing if lime had been added to the soil.

The synthetic gravel-binders were used in part three. Mixing, curing and testing procedures were the same as in part two. Increase in strength, as measured by the CBR tests, was also observed.

The results of the same project were reported by Professor K. B. Woods (3) at the thirty-first Annual Convention of the National Lime Association, with the addition of a series of unconfined compression tests on fine-grained soils. Specimens were prepared in the Proctor mold in the standard manner, compacted at their respective optimum moisture contents determined in the compaction study. Specimens were prepared with soil alone, and with 2 and 5 percent lime added. Three series of unconfined compression tests were run. In one series, the specimens were tested immediately after molding. In the second series, specimens were tested after being removed from the molds, and cured for 7 days on porous discs, which permitted water to rise by capillary action through the specimens. In the third series, the specimens were taken out of the molds and placed in an oven at 140°F for 7 days, after which they were placed on porous discs in water to permit wetting by capillary action. The specimens were loaded in a testing machine until faiılure occurred. The test results indicate that fine-grained materials subjected to the above curing conditions have a marked increase in strength with the addition of 2 and 5 percent lime.

Mr. C. McDowell and Mr. W. H. Moore (4) of the Texas Highway Department conducted experiments on lime-soil mixtures by unconfined compression and triaxial tests.

Seven soils with plasticity indices varying from 18 to 45 were prepared, followed by 7 days of moist-curing. Specimens prepared with soils whose plasticity indices of less than 30 were dried at 140°F, but those prepared with soils whose plasticity indices of greater than 30 were air-dried partially, since complete drying might cause these specimens to crack. Curing was followed by capillary wetting, some for 10 days and some for 30 days. No mention was made as to the moisture content of the specimens at compaction. The ultimate unconfined compressive strength of the specimens were compared with the ultimate strength of an untreated crushed rock specimen which was considered good flexible base material. Results showed that the ultimate compressive strength of untreated specimens were below the ultimate compressive strength of the crushed rock specimens. But the ultimate compressive strengths of all the lime treated specimens were much higher than that of the crushed rock specimens. Percentages of lime used ranges from three to nine percent. The following were the conclusions drawn by McDowell and Moore:

(1) Soil-lime stabilization has a definite application in highway construction for the improvement of certain subgrade and flexible base material.

(2) Many natural soils are suited to lime stabilization. The identical materials proposed for use should be subjected to preliminary physical tests.

(3) Good proportioning and mixing of constituents are advantageous.

(4) Compacting moisture should be at, or slightly below, optimum moisture content for the compactive effort employed.

(5) A high degree of compaction is of critical importance.

(6) Suitable curing procedures are important.

(7) Application of a wearing surface is desirable.

Tests to determine effect of lime on the cohesion of soils were tested by Mr. R. F. Dawson (5) using the Hveem Cohesiometer. A red clayey gravel known to exhibit large volume changes, with liquid limit ranging from fifty to sixty five percent and plasticity index ranging from about twenty five to forty percent were used in this experiment. The six inch diameter specimens, with various percentages of lime added, were compacted with two different compactive efforts: namely 6.63 ft-lbs. per cubic inch and 13.26 ft-lbs.

per cubic inch. The compacted cylinders were placed under a one-psi. all around pressure and permitted to saturate by capillary action through a porous stone. Curing time ranges in age from zero up to four months. Specimens were tested immediately on removal from the moist room. From the test data, it was found that cohesion increases (1) as the time of curing increases, (2) with the increase in compactive effort, and for this particular soil, five percent of lime gave the highest cohesion. Dawson emphasized the benefit of long curing by saying, "Tests for accelerated tensile strength, such as the cohesiometer test, have traditionally been unrealistic for lime stabilization in the construction field unless some unusually long curing periods were used. While the results obtained here show a considerable increase in strength up to a period of four months, they also indicate that the strength increase would be expected to continue far beyond this period; and it might well be expected that a curing period of a six months to a year or even longer would give much higher strength than those currently indicated. The increase in strength with age is due to the fact that lime gains in strength through pozzolanic action and that carbonation takes place slowly".

Experiments with portland cement-soil mixtures were started in the laboratory of the South Carolina State Highway Department in 1932, hoping that it might be used as a base material for light traffic loads (6).

Those initial experiments with portland cement-soil mixtures led to the moulding of samples in the driveway of the laboratory to learn their resistance to weather and traffic. These samples, consisting of top soil and rich sandy clay soil were used with varying amounts of cement. Their resistances to traffic were noticeable greater than that of the raw soil.

The first field experiment, a 528-ft. section of road in good sand clay soil was constructed in 1933. (7) The soil in place was pulverized, and cement applied to the surface at the rate of one bag per linear foot of 20-ft. roadway. Cement and soil were mixed dry, sprinkled, mixed wet, shaped and rolled. After being under traffic, a few pot-holes developed, but there was no indication of raveling or general breakdown.

Mills did not attempt to draw any definite conclusions at that time. He states that, "the action of weather and traffic will in time evaluate the worth of this method of stabilization. The present indication is that treatment of soils with portland cement has appreciable merit and is possible and comparatively economical for many light traffic roads in South Carolina".

Research on various factors influencing physical properties of soil-cement mixtures was carried out by the Portland Cement Associations (8).

A large variety of soils were obtained and nine series of tests were made to determine the influence of various factors upon the compressive strength and resistance to wetting and drying and to freezing and thawing of compacted, hydrated soil-cement mixtures.

In series 1, effect of density on the quality of soil-cement mixture was investigated. The results showed that the effect of density was apparent. Although all the different types of soil-cement mixtures were benefited by increased density, the silty and clayey soil-cement mixtures were benefited the most.

In series 2, the effect of molding moisture content on the quality of soil-cement mixtures was studied.

The wet-dry, freeze-thaw, and compressive strength data, when considered together, indicate that for maximum effectiveness from the cement, sand mixtures should be compacted at optimum moisture content or slightly drier, whereas silty and clayey mixtures should be compacted at moisture contents 1 or 2 percentage points above optimum moisture.

Series 3: During cement-soil pavement base construction, damp mixing may continue for 2 hours or more. A laboratory study of the effect of prolonged damp-mixing was undertaken in this series. The data show that the optimum moisture content increased and the maximum density decreased as the length of mixing time increased. Wet-dry and freeze-thaw test data for these soil-cement specimens show that the losses of weight increased as the length of the damp-mixing period increased. The compressive strength data show consistency in most cases, but in some cases strengths with time of mixing.

In series 4, the effect of the degree of pulverization on the quality of so˙l-cement mixture was investigated. Specimens for wet-dry and freeze-thaw tests were compacted at optimum moisture content, each containing 0 percent, 20 percent, 40 percent of lumps retained on a No. 4 sieve but passing a 1-inch sieve. In one set of specimens (A), air-dry clay lumps were added to the minus-No.-4 mixture which was at AASHO optimum moisture content. Specimens were molded immediately. In the second set (B), air-dry clay lumps were added to the minus-No.-4 mixture, which was also air-dry. Water was then added to the total mix to bring it to optimum moisture content. Thus, in set A the clay lumps had less opportunity to absorb moisture during the mixing period than in set B. It was found that specimens of set A had less resistance to alternate freezing and thawing and wetting and drying than set B. Felt stated, "In some cases complete failure occurred by disruption of the specimens as the dry clay lumps absorbed water and swelled during the curing and testing periods. When the clay lumps were damp (set B) and thus in a swelled condition at the time of inclusion in the test specimens, the unpulverized soil had little harmful effect.

In series 5, a study was made to determine the comparative performance of mixtures made with air-entraining and none-air-entraining cements. Moisture-density relations, compressive strengths, and wet-dry and freeze-thaw test results were sufficiently similar to show that the cements may be used interchangeably in soil-cement construction.

In series 6, tests were made to investigate the effect of cement content on compressive strength and wet-dry and freeze-thaw resistance of soil-cement. Specimens were compacted at optimum moisture content, with cement content of 6 to 34 percent. The compressive strength and resistance to wetting and drying and freezing and thawing increased as the cement content was increased. Depending upon the soil, good quality of mix was obtained with cement contents generally in the range of 8 percent to 14 percent.

In series 7, compressive strength tests were made to study the effect of Type III cement in soil-cement mixtures. Specimens of sandy and silty soil, each with 6, 10, and 14 percent of cement, were molded at AASHO optimum moisture content and maximum density. The optimum moisture content and the maximum density for the mixtures containing Type I or Type III cement were found to be practically the same. Specimens were broken at ages of 1, 2, 3, 4, 6, 7, 10, 14, 28, and 60 days. For both soil types the early-age strengths were consistently greater for Type III than for Type I cement, and nearly all cases the 60-day strengths were also greater for Type III.

Felt states: "Portland cement in quantities less than required for regular soil-cement mixtures has been used to reduce the extent to which the soil shrink, swell, and lose strength. The material thus produced is referred to as cement-modified soil." In series 8 and 9, the effect of various cement contents in altering the properties of fine-grain and granular soils were studied.

In series 8, samples of clay soils to determine of test constants and grain size were compacted at optimum moisture content. These specimens were cured at 100% relative humidity for 7 days. Part of the material was pulverized to pass a No. 10 sieve for hydrometer analysis, and part was pulverized to pass a No. 40 sieve for determining test constants. The results of the tests showed that the addition of cement in quantities less than those required to produce hardened soil-cement mix reduced the plasticity of clayey soils, thus reducing their tendency to shrink, and increased resistance to penetration.

In series 9, the effect of addition of relatively small quantities of cement to granular materials was investigated. The penetration and soniscope tests on specimens at different ages and after various cycles of alternate freezing and thawing were used. The addition of relatively small quantities of cement to granular materials reduced their plasticity and increased their strength. The pulse velocity as indicated by soniscope did not decrease significantly during the freeze-thaw test, showing good resistance to deterioration. The pulse velocities for soil-cement mixture increased with increased cement content and with time of moist curing.

An investigation was made by Mr. J. Leong, Graduate Student at the School of Mines and Metallurgy, Rolla, Missouri, to determine the effect of hydrated lime and portland cement on the physical properties of clay soil for highway base construction (9).

In order to evaluate and compare the changes in physical properties of the selected clay soil with various percentages of hydrated lime and cement additives, the Atterberg limit tests, moisture-density relation test, confined and unconfined compression tests, penetration and durability tests were conducted. T e following were conclusions drawn by Mr. Leong:

(1) Low percentage of calcium hydroxide decrease the PI of the soil to acceptable values (less than 7).

(2) Increase the angle of friction to values comparable to sand, (3) increase the friability of the soil, (4) increase the cohesion to some extent, (5) decreased the volumetric change from 21 percent to 6 percent.

From the same thesis it was evident that the cement additive performed changes of a different nature: (1) up to 10 percent of cement by weight would not bring the P.I. down to acceptable values, (2) the increase in the angle of friction was 30 percent less that of the same amount of Calcium Hydroxide, (3) very little or no effect was noticed on the friability of the soil, (4) increase in the cohesion was up to 40 percent more that by adding the same amount of Calcium Hydroxide, (5) very little effect on the percentage of volumetric change.

It is clear from the study made by Mr. Leong that both the Calcium Hydroxide and the cement impart properties to the soil that are extremely valuable. The next approach was to superimpose some of those improvements, given individually by cement and lime, by adding both materials to the soil. This investigation was made by Mr. R. Frankenberg, Graduate Student at the School of Mines and Metallurgy, Rolla, Missouri, to determine the properties of a soil-lime-cement mixture with standard strength and durability tests (10).

From the results obtained by Mr. Frankenberg in his thesis work, the effects of combined lime and cement additives on the physical properties of soil may be summarized as follo s:

(1) Cement-lime admixtures do not affect the moisture-density relations of the soil to any great extent.

The optimum moisture content is increased slightly, and the maximum dry density is decreased slightly.

(2) When lime is added to the soil it increases the friability and makes it possible to add cement with much less mixing.

(3) Flocculation of the soil reduces the plastic properties of the soil.

(4) Combination of the two additives superimpose their strength characteristics on each other.

(5) Freeze-thaw and wet-dry characteristics are improved greatly with the combination additive.

Friedrich Reinhold, Professor of Highway and Municipal Engineering, Technical University, Darmstadt, Germany, studied the elastic behavior of soil-cement as a function of cement and clay content (11).

Synthetic soils, made by mixing fine sand and clay, were employed for the manufacturing of the test specimens. Four different soil types were prepared which were mixed, at their optimum moisture contents, with three different proportions of portland cement. All specimens were cured in the same manner and for the same period of time before they were tested. The stress-strain diagrams of all the different soil-cement compositions tested in compression. On the basis of the performed tests it was established that soil-cement was basically similar to portland cement concrete, with respect to stress-strain relationship. The following important results were drawn by Reinhold: (1) determinant for the elastic behavior of soil-cement is its compressive strength; (2) this can be influenced by densification, cement content, water content, and clay content; (3) up to one-third of the compressive strength, one can assume a linear stress-strain diagram for soil-cement; (4) dependable values for moduli of elasticity and sufficiently accurate Poisson numbers are available for the range of practical application; and (5) they are functions of the stress and depend strongly upon cement content and on the clay content.

An investigation was made by Mr. Earl J. Felt and Mr. Melvin S. Abrams to present data showing the range in strength and elastic properties for soil-cement mixtures made of different soils (12).

The soil-cement mixtures investigated were made of four soils of particular interest for road and runway base construction. Structural properties were determined for soil-cement mixtures made of the four soils mixed with at least three different cement contents each. All test specimens were molded at ASTM optimum moisture content and maximum density. The soil-cement mixtures for all test specimens were prepared by mixing the air-dry soil and cement. Specimens were cured in a fog room until tested except in a few cases where the specimens were dried after initial moist curing. Data were presented in this report on modulus of elasticity, modulus of rupture, Poisson's ratio, and compressive strength on several soil-cement mixtures. The modulus of elasticity was obtained by the sonic method and by static methods in bending and in compression. The effect of size and shape of specimen on compressive strength was explored. Flexural tests on 3 by 3 by 11¼ inch beams were made immediately after removal of specimens from the moist room following 7, 28, and 90 days of curing; compressive strength tests and modulus of elasticity tests on cylinders were made at these same ages, and in addition, compression tests were made on cylinders after 365 days moist curing. A number of compressive strength and modulus of elasticity tests were made on 28-day cylinders that had been dried after initial moist curing.

The data obtained showed that the modulus of rupture, compressive strength, and modulus of elasticity of soil-cement mixtures varied greatly depending upon soil type, cement content, age, and type of curing. In all cases the test values increased as the cement content was increased and as the time of moist curing was increased. The soil type had a major influence on test values. Drying of moist-cured soil-cement specimens before testing had also a major influence on compressive strength and modulus of elasticity in compression. However, the static modulus of elasticity of the specimens that were dried before testing was less than that of companion moist-tested specimens. Poisson's ratio for the soil-cement mixtures varied considerably.

Laboratory investigation was made by Mr. Gleen G. Balmer on the shear strength and elastic properties of soil-cement mixtures under triaxial loading (13).

Triaxial shear results were obtained by laboratory tests on specimens molded from two granular and two fine-grain soils mixed with various amounts of portland cement at optimum moisture and maximum density. The cement contents of these specimens varied from 0 to 16 percent by weight of dry soil. The cylinders were moist cured 7, 28, and 90 days except for a few specimens that were given special curing. The analyses of the test results showed that the coefficient of internal friction was relatively constant for cement-treated specimens of each soil regardless of cement content and age but varied with the type of soil. The cohesive strength increased with cement content, age and type of soil. The rate of increase in strength with cement content was greater for the granular-soil-cement mixtures than for the silty soil-cement mixtures. The modulus of elasticity computed from the deformation measurements increased with cement content and age. Although drying the specimens increased the strength, it decreased the modulus of elasticity. Poisson's ratio seemed to be independent of cement content and age.

MATERIALS

Materials used in this research were soil, hydrated lime and cement.

Soil: All the soil used in the experiments was obtained from a farm owned by Mr. John Heagler, Sr., located about seven miles southeast of Rolla on Highway U. S. 72. The soil is from the B horizon, and may be classified as a reddish yellow Podzolic soil. The reason for selecting the soil from the B horizon is clearly stated by Mr. M. C. Spangler (14). He states that, "this lower horizon usually contains finer-grained materials and often is much more surface-chemically active and unstable than the soil either above or below it. These characteristics render the B horizon extremely important in highway and airfield design and construction or other work in which the foundations are located near the ground surface."

The specific gravity of the soil was determined in accordance with the Standard Method of Test for Specific Gravity of Soils, ASTM Designation: D854-52 (15), and was found to be 2.60.

A liquid limit test conducted in accordance with the tentative method of test for liquid limit of soils, ASTM Designation: D423-54T (16) and was found to be 35.5%.

The plastic limit was determined in accordance with the Tentative Method of Test for Plastic Limit and Plasticity Index of Soils, ASTM Designation: D424-54T (17), and was found to be 19.0%. Plasticity Index = 35.5 19.0 - 16.5.

Grain soil analysis of the soil was performed in accordance with ASTM Designation: D422-54T (18), and the grain size accumulation chart was plotted in Figure 1. This soil, with eighty-six percent passing No. 200 sieve, a Liquid Limit of 35.5% and a Plastic Limit of 19.0, is classified as A-6 by the American Association of State Highway Officials Classification (19), and it is described as a "plastic clay soil usually having seventy-five percent or more passing the No. 200 sieve. Materials of this group have a high volume change between wet and dry states. This group index values range from 1 to 16, with increasing values indicating the combined effect of increasing plasticity indices and decreasing percentages of coarse material."

The PCA Soil Primer (20) describes group A-6 soils as "soils possessing little internal friction and have low stability at the higher moisture contents. These soils are not suitable for use as subgrades under thin flexible base courses or bituminous surfaces because of large volume changes that are caused by moisture changes, and the loss of bearing power after the entrance of moisture. The heavier A-6 courses may require insulating courses to prevent excessive concrete pavement distortion or mud-pumping. All flexible-type bases must have an insulating courses for A-1 or A-2 soils, stone chips, etc., or soil cement to prevent the clay from working into the flexible base, thus destroying its load carrying capacity."

Hydrated Lime: The hydrated lime used in the experiments was ordinary commercial grade, manufactured by Ash Grove Lime and Cement Company at Kansas City, Missouri.

Portland Cement: All cement used in the experiments was Type 1 Portland Cement, manufactured by Ash Grove Lime and Cement Company at Kansas City, Missouri.

EXPERIMENTS AND EQUIPMENT

In order to present data showing the range in strength and elastic properties of the selected clay soil by admixing of hydrated lime and cement; and to show the interrelationship between these properties the following experiments were performed:

(1) Moisture-Density Relation Test

(2) Modulus of Rupture Test

(3) Dynamic Modulus of Elasticity Test

(4) Dynamic Poisson's Ratio Test

The above experiments were performed with: (1) untreated soil, (2) soil with 4, 6, 8, and 12 percent cement additive, (3) soil with a 3 percent lime additive and 0, 4, 6, 8, and 12 percent cement additive, (4) soil with a 6 percent lime additive and 0, 4, 6, 8, and 12 percent additive, (5) soil with a 9 percent lime additive and 0, 4, 6, 8, and 12 percent cement additive by weight.

The soil-cement-lime mixtures (herein often referred to as SCL) for test specimens were prepared by mixing the air dry soil passing a No. 4 sieve with cement and lime. The mixtures were first mixed until uniform in color and then mixed for three minutes in a Lancaster Counter Batch Mixer (Figure 2) with the water required to bring the mixtures to optimum moisture contents.

Beam specimens 2 by 4 by 8 inch were used for determining modulus of rupture, dynamic modulus of elasticity, and dynamic Poisson's ratio. The proper weight of the SCL mixture, at optimum moisture content and maximum density, to produce 2 by 4 by 8 inch beam was compacted in the molds at the Ceramic Department (Figure 3). The apparatus used for molding specimens was manufactured by The Hydraulic Press MFG Co., Columbus, Ohio. Specimens were then placed in the moist room with protection from free water until tested (Figure 4). During the period between removal from the moist room and testing, the specimens were kept moist under wet burlap. Excellent beam specimens having sharp corners were obtained.

<u>Test for Moisture Density Relations</u>: ASTM Designation: D558-44 (21). The soil used for this test was air-dry soil passing a No. 4 sieve. The apparatus consisted of a cylindrical metal mold having a capacity of 1/30 cu. ft. with an internal diameter of 4.0 inches and a height of 4.6 inches; a metal rammer having a 2-in. diameter circular face and weighing 5.5 lb; a sleeve and hydraulic jack for removing compacted specimens from the mold; a scale sensitive to 0.01 lb.; a 100-g. capacity balance sensitive to 0.1 g.; and a lancaster counter batch mixer for mixing lime, cement, soil, and water.

The procedure used for finding the optimum moisture content of the various soil-cement-lime mixtures was in accordance with ASTM Designation: D558-44. The results of these tests and graphs are shown in Appendix F. The optimum moisture content and the maximum dry density for various admixtures are shown in Table I.

Test for Modulus of Rupture: ASTM Designation: C293-54T (22). The modulus of rupture of the 2 by 4 by 8-in. beams was determined using center-point loading. The beams were broken by loading on their sides with respect to their position as molded (Figure 5). Suggestions given in ASTM Method C293-54T, Tentative Method of Test for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), were followed in making the flexure test.

The results of the modulus of rupture tests are shown in Table II, and graphs of the results are shown in Appendix A.

Test for Dynamic Modulus of Elasticity: ASTM Designation: C215-55T (23). The dynamic modulus of elasticity was calculated from the fundamental transverse frequency, weight, and dimensions of the 2 by 4 by 8-in. beams before breaking them in flexure. Sonic testing apparatus (Figure 6, 7) was used to measure the fundamental frequency of the SCL specimens. I t consists of a cathode-ray oscillograph, an audio oscillator, an amplifier, a driver to produce the vibration and a pick-up (Figure 8, 9).

The oscillograph was manufactured by Allen B. DuMont Laboratories, Inc., Passoic, New Jersey, Type 164E.

The audio oscillator was manufactured by Hewlet Packard, Palo Alto, California.

The driver is a magnetic speaker with a stem connected to the voice cell. This is a product of the Quam Company, Chicago, Illinois.

The pick-up is a simple phonograph pick-up manufactured by the Astatic Corporation, Conneaut, Ohio.

Equations relating to this method are given in ASTM Method C215-55T, Tentative Method of Test for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens.

These equations may be reduced to:

$$E = CWn^2$$

where:

E = dynamic modulus of elasticity, psi,

W = weight of specimen, lb,

n = fundamental transverse frequency, cps,

C = a factor (for prisms) = $0.00245 \dfrac{L^3 T}{bt^3}$ sec.^{2} per psi,

L = length of specimen, in.,

t,b = dimensions of cross-section of prism, in., t being in the direction in which it is driven, and

T = a correction factor which depends on the ratio of the radius of gyration, (which for a prism is t/3.464), to the length of the specimen, L, and on Poisson's ratio (taken at 0.25).

The results of the dynamic modulus of elasticity tests are shown in Table III, and graphs of the results are shown in Appendix C.

Test for Dynamic Poisson's Ratio: ASTM Designation: C215-55T (24). Dynamic Poisson's ratio for the beam specimens was calculated from the following formula using procedures given in ASTM Method C215-55T.

$$= \frac{E_d}{2G} - 1$$

Where:

= dynamic Poisson's ratio

E_d = dynamic modulus of elasticity, psi, and

G = modulus of rigidity, psi.

Dynamic modulus of rigidity (G) was calculated from the fundamental torsional frequency, weight, and dimensions of the test specimen as follows:

$$G = BW\ (n^{11})^2$$

Where:

W = weight of specimen in lbs.,

n^{11} = fundamental torsional frequency in cycles per second,

B = $\frac{4LR}{gA}$ sec^2 per sq. in.

L = length of specimen in inches,

R = shape factor (which is $\frac{a/b + b/a}{4a/b - 2.52\ (a/b)^2 + 0.21\ (a/b)^6}$

for a rectangular prism whose cross-sectional dimensions are a and b inches, with a less than b),

g = gravitational acceleration, (386.4 in. per sec.^{2}) and,

A = cross sectional area of test specimen in square inches.

MIXTURE	MAX. DRY DENSITY LB. PER CU. FT.	OPTIMUM MOISTURE CONTENT PERCENT
Natural Soil	102.8	19.6
Soil ≠ 4% Cement	100.4	20.5
Soil ≠ 6% Cement	102.4	20.6
Soil ≠ 8% Cement	101.8	19.7
Soil ≠ 12% Cement	104.3	21.8
Soil ≠ 3% Lime	98.4	21.9
Soil ≠ 3% Lime ≠ 4% Cement	98.1	22.7
Soil ≠ 3% Lime ≠ 6% Cement	99.3	21.6
Soil ≠ 3% Lime ≠ 8% Cement	100.7	21.1
Soil ≠ 3% Lime ≠ 12% Cement	100.4	22.5
Soil ≠ 6% Lime	97.2	22.4
Soil ≠ 6% Lime ≠ 4% Cement	96.9	22.6
Soil ≠ 6% Lime ≠ 6% Cement	97.8	22.4
Soil ≠ 6% Lime ≠ 8% Cement	98.6	22.1
Soil ≠ 6% Lime ≠ 12% Cement	99.1	22.7
Soil ≠ 9% Lime	96.3	23.7
Soil ≠ 9% Lime ≠ 4% Cement	95.9	23.5
Soil ≠ 9% Lime ≠ 6% Cement	96.4	23.2
Soil ≠ 9% Lime ≠ 8% Cement	97.4	23.1
Soil ≠ 9% Lime ≠ 12% Cement	98.2	23.4

TABLE I

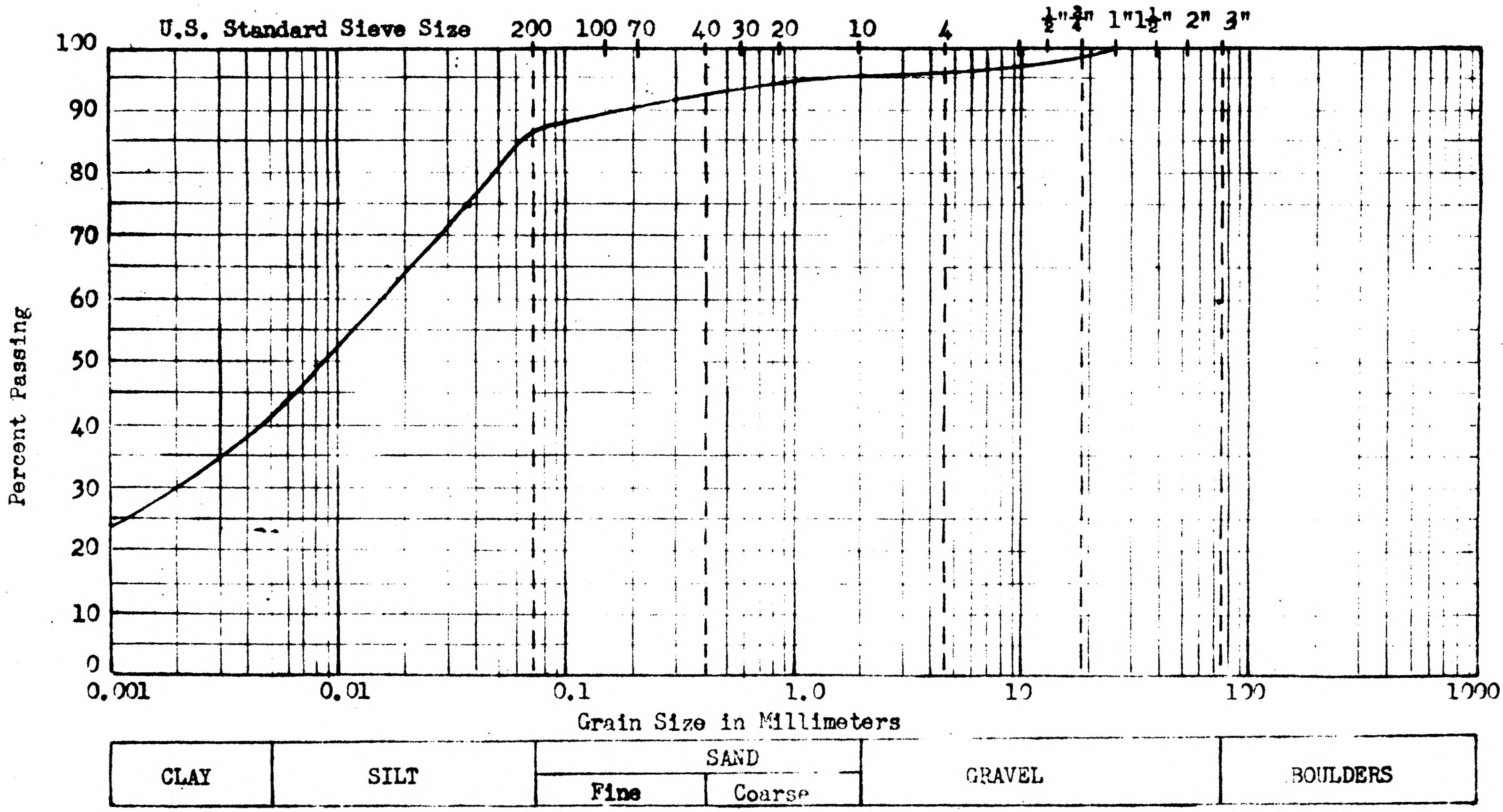


FIGURE 1

GRAIN SIZE ACCUMULATION CHART

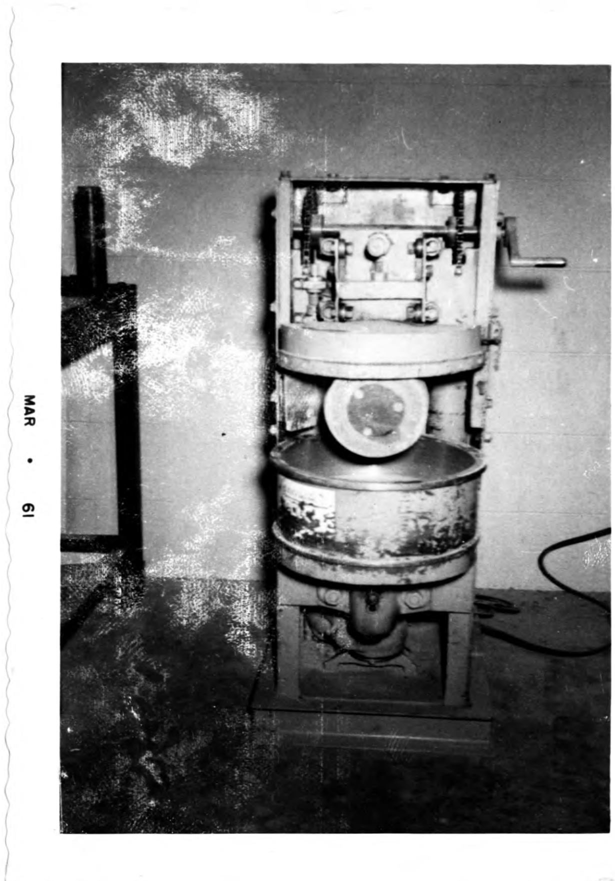


FIGURE 2

LANCASTER COUNTER BATCH MIXER

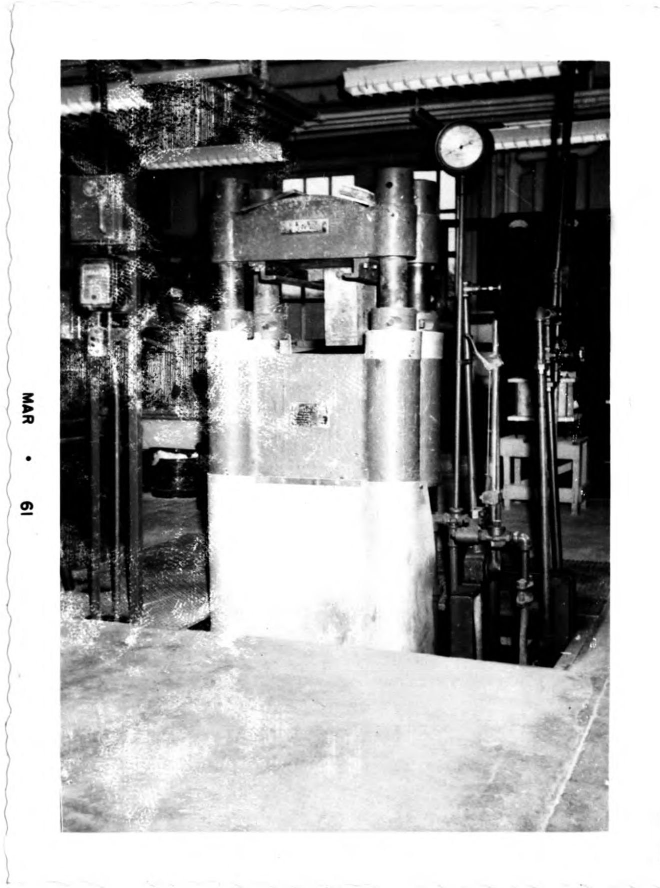


FIGURE 3
APPARATUS USED FOR MOLDING SPECIMENS

FIGURE 4
TEST SPECIMENS IN MOIST ROOM

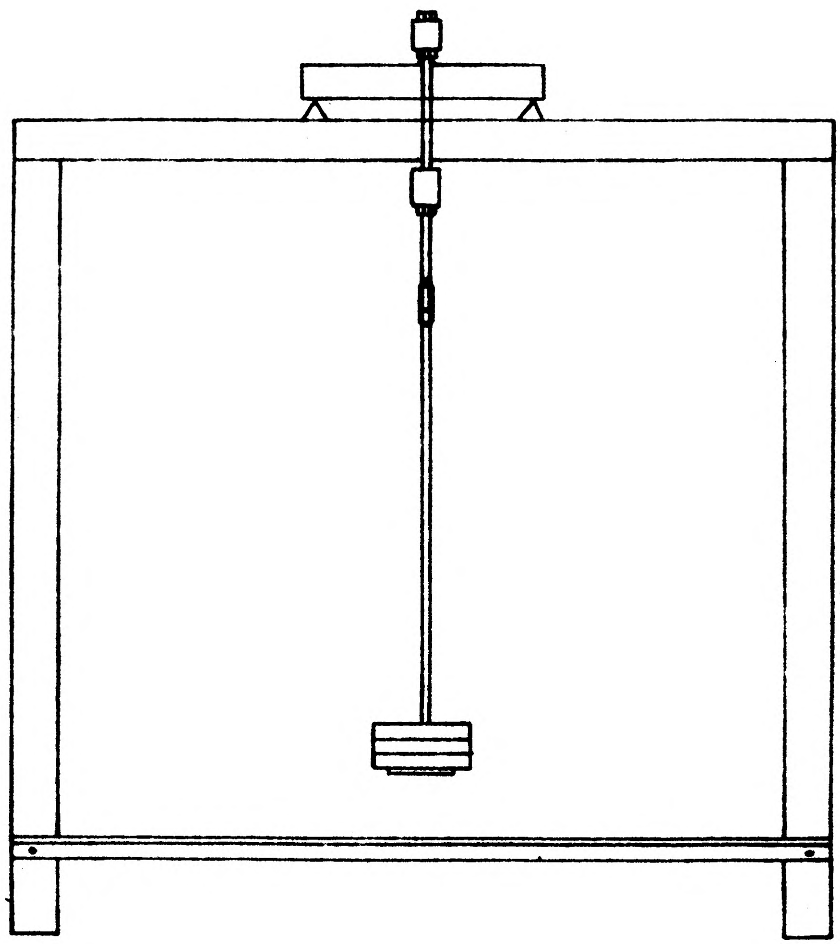


FIGURE 5
BREAKING THE SPECIMENS IN FLEXURE

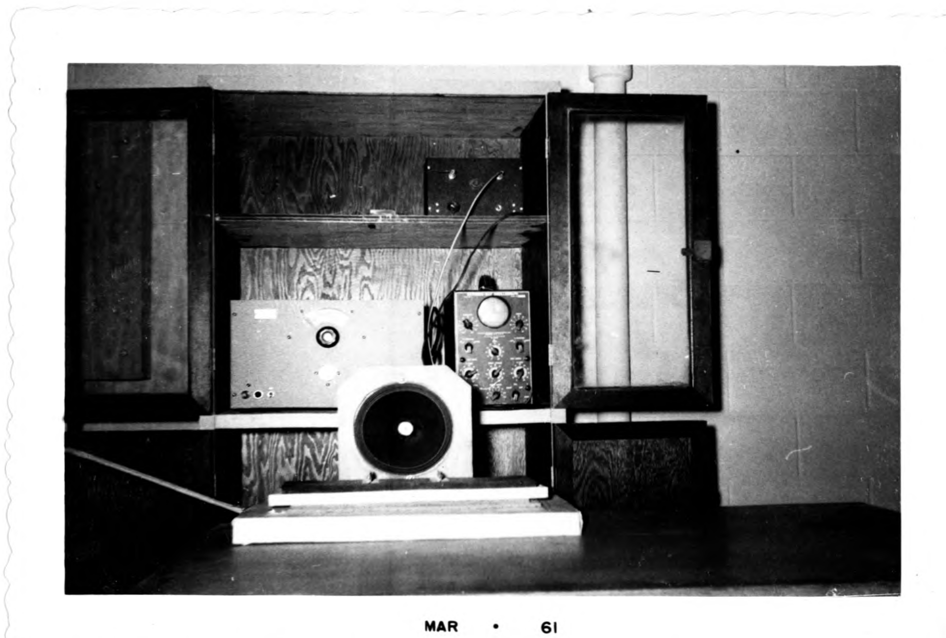


FIGURE 6
SONIC TESTING APPARATUS

FIGURE 7
SONIC TESTING APPARATUS IN OPERATING POSITION

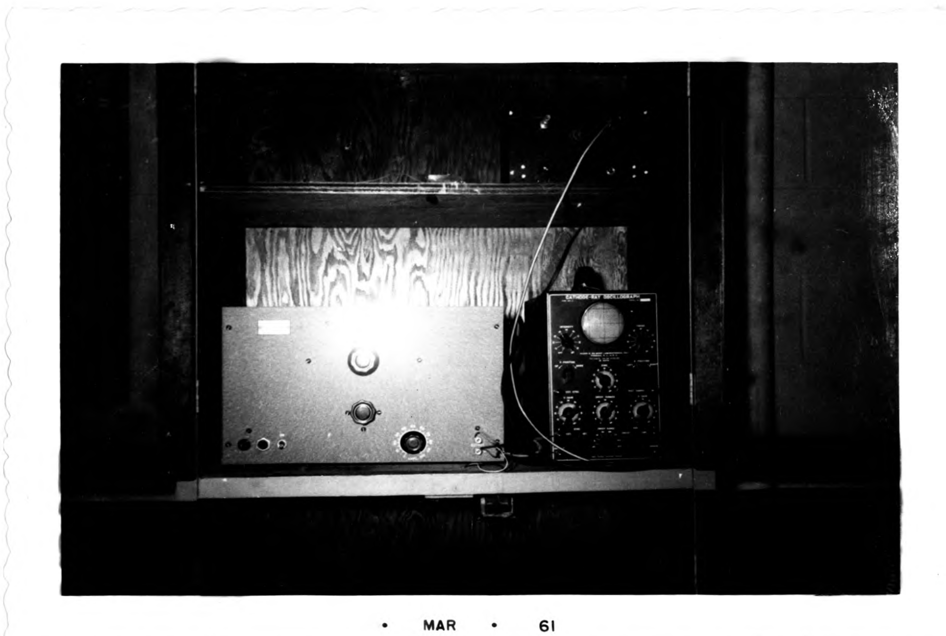


FIGURE 8

CATHODE-RAY OSCILLOGRAPH, AUDIO OSCILLATOR, AMPLIFIER

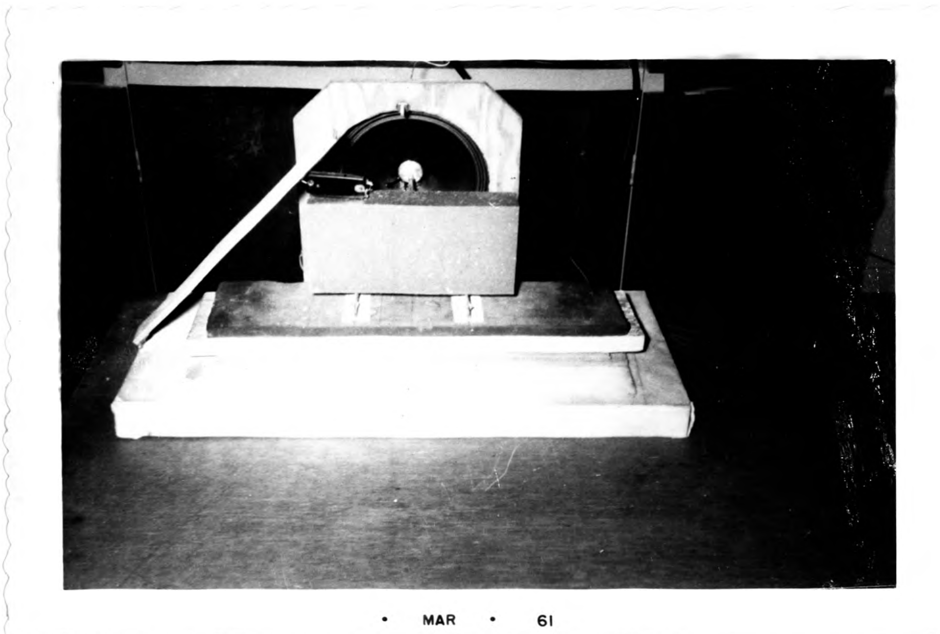


FIGURE 9
DRIVER, PICK-UP, AND THE SPECIMEN

DISCUSSION OF RESULTS

This paper covers a laboratory investigation of the flexural strength and elastic properties of soil-cement-lime mixtures.

Several investigations have been performed on structural and physical properties of soil-cement and soil-lime mixtures. From the results of these studies, it can generally be said that the elastic behavior of soil-cement and soil-lime mixtures is a function of mixture strengths. All factors that influence the strength properties also determine the elastic behavior of soil-cement and soil-lime. Studies are now in progress on elastic properties of soil-cement and soil-lime pavements which will improve construction practices and lead to rational design procedures.

Flexural tests, dynamic modulus of elasticity and dynamic Poisson's ratio tests on beams were made immediately after removal of specimens from the moist room following 7 and 28 days of curing. During the mixing of lime-cement and soil, it was apparent that the much sought for friability was obtained and that the cement was much more uniformly dispersed through the mix than was ever possible in this soil when it was the only additive. Lime-cement admixtures did not affect the moisture-density relationships to any great extent. The optimum moisture content was increased slightly and maximum dry density was decreased slightly. One extra specimen was molded of each mix for check tests as needed.

Appendix A contains graphs obtained from the modulus of rupture tests on cured specimens. Data tabulated in Table II on the modulus of rupture after 7 and 28 days of moist curing show that the modulus of rupture varies greatly depending upon cement content, lime content, combined cement and lime contents and age of curing. The modulus of rupture of clay soil increased from 32 psi. without cement and lime additives to 243 psi. with 9 percent lime and 12 percent cement additives after 7 days moist curing and 300 psi. after 28 days moist curing. From an examination of the data tabulated in Table II and the graphs in Appendix A, it is observed that the use of either additive increases the modulus of rupture of the clay soil and that increase in cement content gave better results for the same percentage of added material. Addition of 3 percent lime to the natural soil increased its modulus of rupture from 32 psi. to 51 psi. after 7 days moist curing and to 66 psi. after 28 days moist curing, the modulus of rupture of the soil-cement increased to 75 psi. after 7 days moist curing and 93 psi. after 28 days moist curing with 4 percent cement additive. The increase in modulus of rupture for 3 percent lime additive was 19 psi. after 7 days moist curing and 33 psi. after 28 days moist curing. For 4 percent cement additive these values are 43 psi. after 7 days moist curing and 60 psi. after 28 days moist curing. It is clear

MIXTURE	AVE. OF 3 SPECS. MODULUS OF RUPTURE. PSI. 7 DAYS	AVE. OF 3 SPECS. MODULUS OF RUPTURE. PSI. 28 DAYS
Natural Soil	32.14	33.01
Soil ⨍ 4% Cement	75.04	93.20
Soil ⨍ 6% Cement	96.34	118.46
Soil ⨍ 8% Cement	113.20	144.52
Soil ⨍ 12% Cement	147.28	193.16
Soil ⨍ 3% Lime	51.24	66.26
Soil ⨍ 3% Lime ⨍ 4% Cement	92.18	120.34
Soil ⨍ 3% Lime ⨍ 6% Cement	116.12	146.10
Soil ⨍ 3% Lime ⨍ 8% Cement	135.06	171.04
Soil ⨍ 3% Lime ⨍ 12% Cement	174.46	221.0
Soil ⨍ 6% Lime	64.22	91.12
Soil ⨍ 6% Lime ⨍ 4% Cement	114.42	147.34
Soil ⨍ 6% Lime ⨍ 6% Cement	141.0	176.41
Soil ⨍ 6% Lime ⨍ 8% Cement	165.21	206.63
Soil ⨍ 6% Lime ⨍ 12% Cement	216.32	268.31
Soil ⨍ 9% Lime	73.11	108.24
Soil ⨍ 9% Lime ⨍ 4% Cement	133.20	173.16
Soil ⨍ 9% Lime ⨍ 6% Cement	162.32	203.0
Soil ⨍ 9% Lime ⨍ 8% Cement	188.11	235.28
Soil ⨍ 9% Lime ⨍ 12% Cement	243.63	300.8

MIXTURE	AVE OF 3 SPECS. MODULUS OF ELASTICITY 10^6 PSI. 7 DAYS	AVE OF 3 SPECS. MODULUS OF ELASTICITY 10^6 PSI. 28 DAYS
Natural Soil	0.652	0.654
Soil + 4% Cement	0.078	1.115
Soil + 6% Cement	1.140	1.334
Soil + 8% Cement	1.290	1.512
Soil + 12% Cement	1.572	1.851
Soil + 3% Lime	0.796	0.932
Soil + 3% Lime + 4% Cement	1.105	1.260
Soil + 3% Lime + 6% Cement	1.251	1.453
Soil + 3% Lime + 8% Cement	1.392	1.601
Soil + 3% Lime + 12% Cement	1.671	1.952
Soil + 6% Lime	0.982	1.110
Soil + 6% Lime + 4% Cement	1.226	1.420
Soil + 6% Lime + 6% Cement	1.380	1.580
Soil + 6% Lime + 8% Cement	1.521	1.741
Soil + 6% Lime + 12% Cement	1.802	2.083
Soil + 9% Lime	1.118	1.301
Soil + 9% Lime + 4% Cement	1.424	1.603
Soil + 9% Lime + 6% Cement	1.553	1.775
Soil + 9% Lime + 8% Cement	1.695	1.943
Soil + 9% Lime + 12% Cement	1.952	2.261

TABLE III

from this discussion that almost the same amount of cement and lime additives increased the strength values of the soil considerably. But the increase in the modulus of rupture for 4 percent cement additive was approximately twice the increase caused by 3 percent lime additive. This ratio of increments of modulus of rupture was generally found to exist for increased percentages of cement and lime additives.

Appendix B contains graphs of modulus of rupture versus various percentages of cement with a constant percent lime additive. As can be seen from these graphs the modulus of rupture of soil-cement-lime mixtures increases in an orderly fashion with an increase in cement and lime contents. The relationships were almost linear. Thus it is possible to interpolate and predict values for the strength properties when incomplete data are available.

Appendix C contains graphs of 7 and 28 day modulus of rupture versus percent additive. A study of these graphs indicates that on the basis of total additive the lime does not add to the system at 7 days. That is 7 day modulus of rupture of 3 percent lime plus 8 percent cement is equal to or less than 7 day modulus of rupture of 4 percent cement plus 10 percent lime, 6 percent cement plus $5\frac{1}{2}$ percent lime, 8 percent cement plus 3 percent lime and 10 percent cement plus 1 percent lime. The same holds true on the basis of 28 day strength.

Dynamic modulus of elasticity values, determined just prior to testing beams in flexure, are shown in Table III. The values of the dynamic modulus of elasticity ranged from 0.65×10^6 psi. for natural soil to 2.26×10^6 psi. for soil with 9 percent lime and 12 percent cement additives. Graphical representations of the dynamic modulus of elasticity tests results are shown in Appendix D. A study of the graphs in Appendix D indicates that the modulus of elasticity also varies greatly depending upon cement content, lime content, combined cement and lime contents and age of curing. The use of either additive increased the modulus of elasticity values of the soil. But cement content gave better results for the same percentages of added material.

Appendix E contains the graphs of modulus of elasticity versus percent cement with a constant percent of lime additive. As can be seen from the graphs in Appendix E the modulus of elasticity increased in an orderly fashion with lime and cement contents. The relationships were nearly linear for soil-cement-lime mixtures. This relationship may make it possible to interpolate and predict values for the modulus of elasticity values when incomplete data are available.

Appendix F contains graphs of 7 and 28 day modulus of elasticity versus percent additive. From an examination of the graphs in Appendix F, it is observed that the cement is more effective alone than combined additives in the same quantity. That is 12 percent cement alone gives better modulus of elasticity values than any combination of lime and cement up to a total of 12 percent additive and this appears to hold throughout the scale.

Modulus of rupture and modulus of elasticity of concrete at 7 days of 300 psi. and 3×10^6 psi. are considered a criteria of acceptance in highway work. With sufficient additive the values of modulus of rupture and modulus of elasticity are of significant magnitude and it would appear practical to include this fact in design criteria. For this particular soil 6 percent lime and 8 percent cement additives gave better results than the other percentages of the same additives if the problem is considered from the economical point of view.

The relation of the modulus of rupture of the soil-cement-lime mixtures to the dynamic modulus of elasticity is shown in Appendix G. The graphs in Appendix G show 7 and 28 days values of modulus of rupture of soil versus 7 and 28 days values of modulus of elasticity of soil for the same percentage of additives. The interrelationship between the modulus of rupture and modulus of elasticity varied in an orderly fashion also, making it possible to estimate one property when another is known.

Dynamic Poisson's ratio was determined from the fundamental transverse and torsional frequencies of the beams. Values so computed exhibited a random variation with cement and lime contents and age of curing; and were in the range of 0.26 to 0.33.

SUMMARY AND CONCLUSIONS

Flexural strength and elastic properties of soil-cement-lime mixtures have been determined. The data and information presented might aid engineers to use and design SCL to take advantage of its structural properties, not only for road construction, but also for other types of construction. The comments which follow summarize the general conclusion derived from the results of the various tests.

(1) The modulus of rupture of SCL mixtures varies greatly depending upon lime and cement contents and age of curing. In all cases test values increased as the lime and cement contents were increased and as the time of moist curing was increased.

(2) The modulus of rupture increased in an orderly fashion with an increase in cement and lime contents. The relationships are nearly linear.

(3) 7 and 28 day modulus of rupture is not materially reinforced by the addition of lime instead of cement on a total additive basis. That is [illegible] percent cement is even a little better than 8 percent cement and 3 percent lime. Inversely there is no measurable loss involved and since lime is slightly cheaper than cement some ecoomy may be expected. There is also the fact that the lime aids in getting the cement into the soil.

(4) The modulus of elasticity increased with cement and lime contents. The modulus of elasticity also increased with age of curing.

(5) Modulus of elasticity increased in an orderly fashion with an increase in cement and lime contents. The relationships are almost linear.

(6) 7 and 28 day modulus of elasticity values (Graphs 25-26, Appendix F) indicate that the cement is more effective alone than combined additives in the same quantity. That is 12 percent cement alone gives better modulus of elasticity values than any combination of lime and cement up to a total of 12 percent additive and this appears to hold throughout the scale. Again the value of flocculation must outweigh more effective adhesion to permit lime to be used.

(7) Poisson's ratio of SCL mixtures exhibited a random variation with cement and lime contents and age of curing.

(8) Modulus of rupture and modulus of elasticity tests values for the moist cured SCL mixtures almost varied linearly with cement and lime factors. Thus it is possible to interpolate and predict values for the various strength and elastic properties when incomplete data are available.

(9) The interrelationship between the modulus of rupture and modulus of elasticity varied in an orderly fashion, making it possible to estimate one property when another is known.

(10) It can be said that the elastic behavior of SCL is a function of its strength. All factors that

influence the strength properties also determine the elastic behavior of mixture.

(11) Modulus of rupture and modulus of elasticity of concrete at 7 days of 300 psi. and 3.10^6 psi. are considered a criteria of acceptance in highway work. With sufficient additive the values of modulus of rupture and modulus of elasticity of soil are of a significant magnitude and it would appear practical to include this fact in design criteria.

As an application of the test values obtained in this thesis to a design criteria the following problem is an example.

If it is desired to design a pavement for light traffic on a soil which has a CBR value equal to 4 with a base course for which E = $1.5.10^6$ psi., R (modulus of rupture) = 200 psi. and μ=(Poisson's ratio) = 0.25, we may use Westergaard's rigid pavement design formulae. Westergaard's formulae for rigid pavement design are shown below:

$$\sigma_c = \frac{3P}{h^2}\left[1 - \left\{\frac{12(1-\mu^2)k}{Eh^2}\right\}^{0.15}\left\{a\sqrt{2}\right\}^{0.6}\right]$$

$$\sigma_e = \frac{0.529P}{h^2}\left[1 + 0.54\mu\right]\left[\log_{10}\left\{\frac{Eh^3}{kb^4}\right\} - 0.71\right]$$

$$\sigma_i = \frac{0.275P}{h^2}(1-\mu)\log_{10}\left\{\frac{Eh^3}{kb^4}\right\}$$

where:

E = Modulus of elasticity for concrete (psi.)

μ = Poisson's ratio for concrete

k = Modulus of subgrade reaction (#/cu. in.)

h = Thickness of the base (in.)

P = Total load exerted by one wheel (lb.)

a = Radius of equivalent circle of contact area (in.)

$b = \sqrt{(1.6a^3 - h^2)} - 0.675h$ when $a < 1.724h$

$b = a$ when $a > 1.724h$

σ_c = Maximum tensile stress in the concrete at the top of the slab near a corner (lb./sq. in.)

σ_i = Maximum tensile stress in the concrete at the bottom of the slab at an interior location, directly under the center of an applied load (lb./sq. in.)

σ_e = Maximum tensile stress in the concrete at the bottom of the slab along an unbroken edge (lb./sq. in.)

Applying the values:

$E = 1.5 . 10^6$ psi.

R = 200 psi.

$\mu = 0.25$

k = 125 #/cu. in.

P = 7000# (wheel load)

a = 6 in.

to Westergaard's formulae and solving the equations by trial and error method for "h" we get a satisfactory lime-cement stabilized base thickness of 6 in. as shown in Figure A.

If we design a flexible pavement on the same subgrade soil under same conditions by using CBR method we get a pavement as shown in Figure B.

As it is evident from these two figures the total depth of pavement which was designed by using Westergaard's formulae was 5 in. less than the total depth of the pavement that was designed by using CBR method. So an economy may be expected from the cost of labor in favor of the first design procedure.

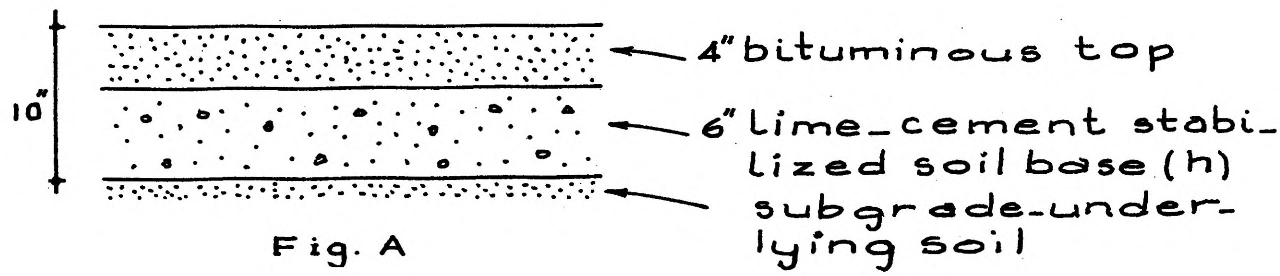


Fig. A

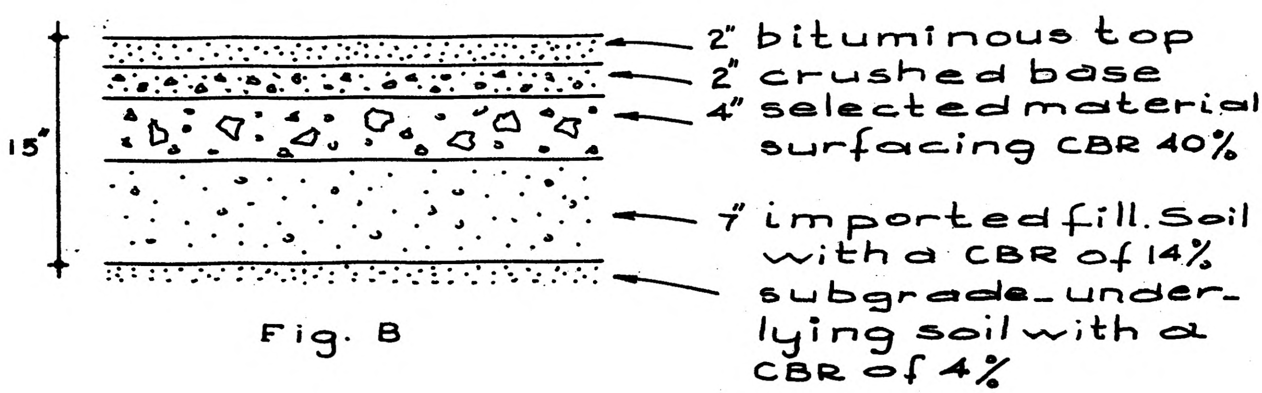
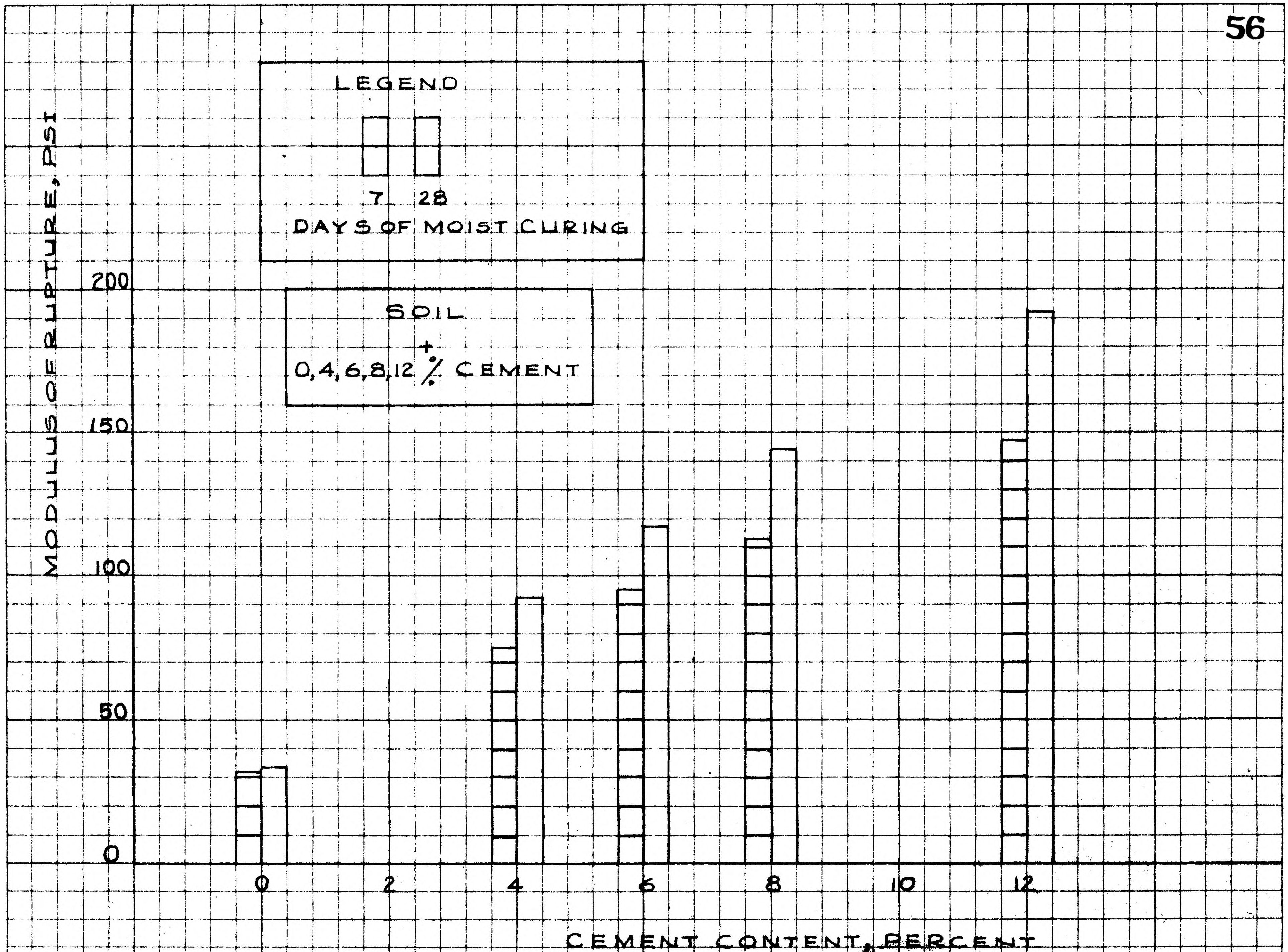


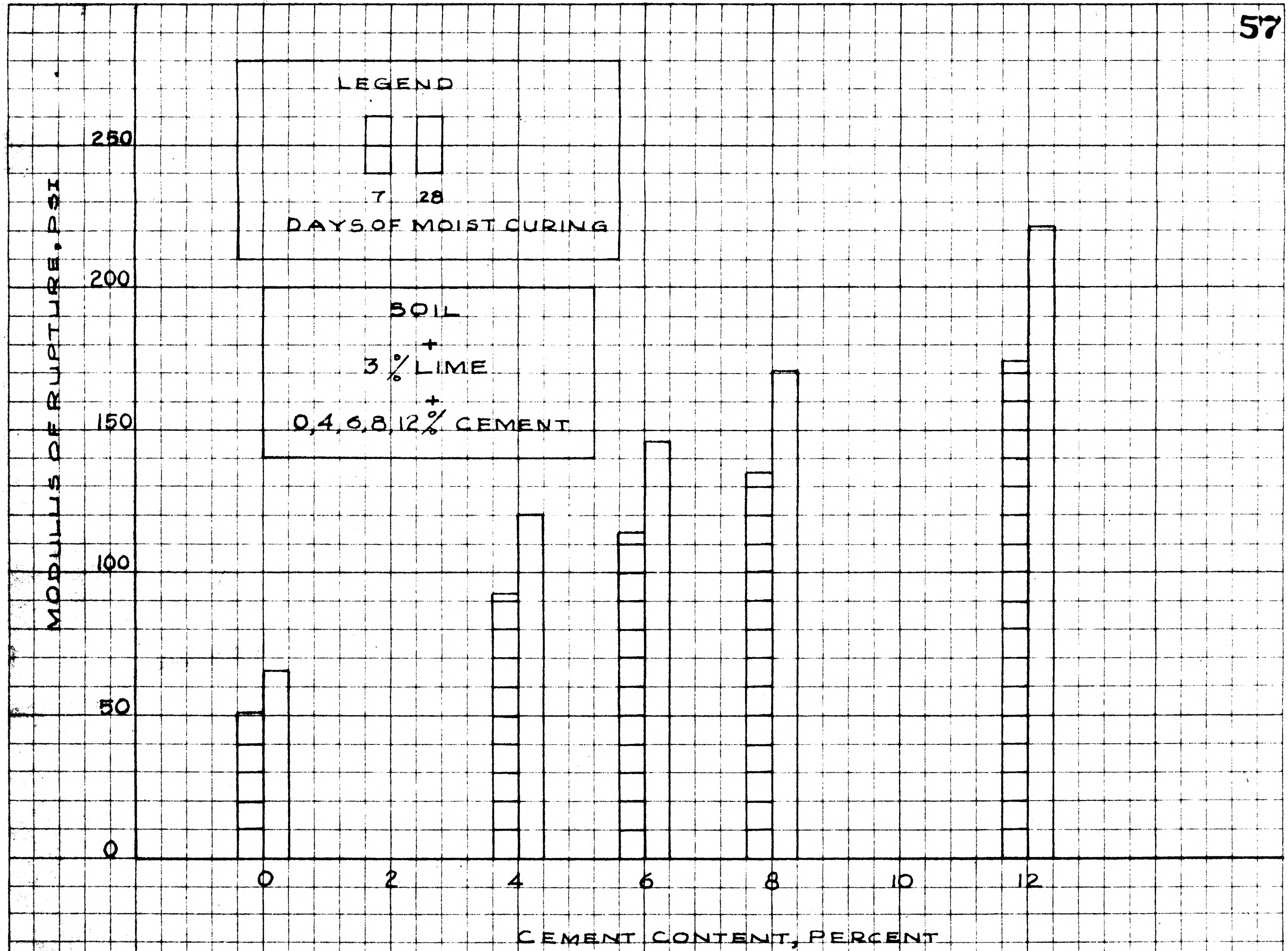
Fig. B

The conclusion drawn in this paper refer to the soil-lime-cement mixtures tested. It is not intended that these results should eliminate the necessity of laboratory tests for individual soils. Therefore, for any particular soil encountered, some laboratory investigation must be conducted before any field work is attempted.

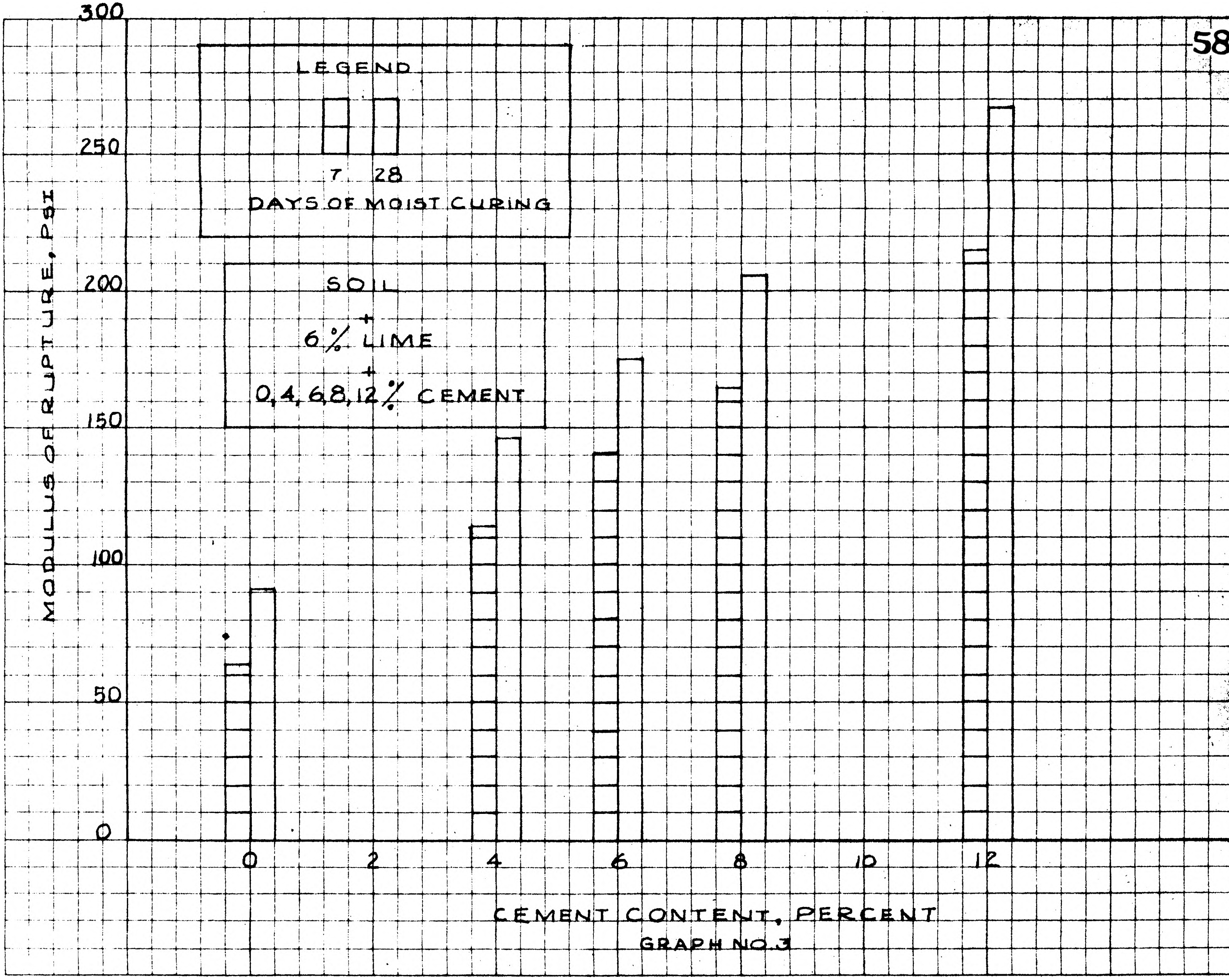
APPENDIX A
DATA OF MODULUS OF RUPTURE TEST


LEGEND
7
28
DAYS OF MOIST CURING
SOIL
+
0,4,6,8,12 % CEMENT
MODULUS OF RUPTURE, PSI
0
50
100
150
200
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

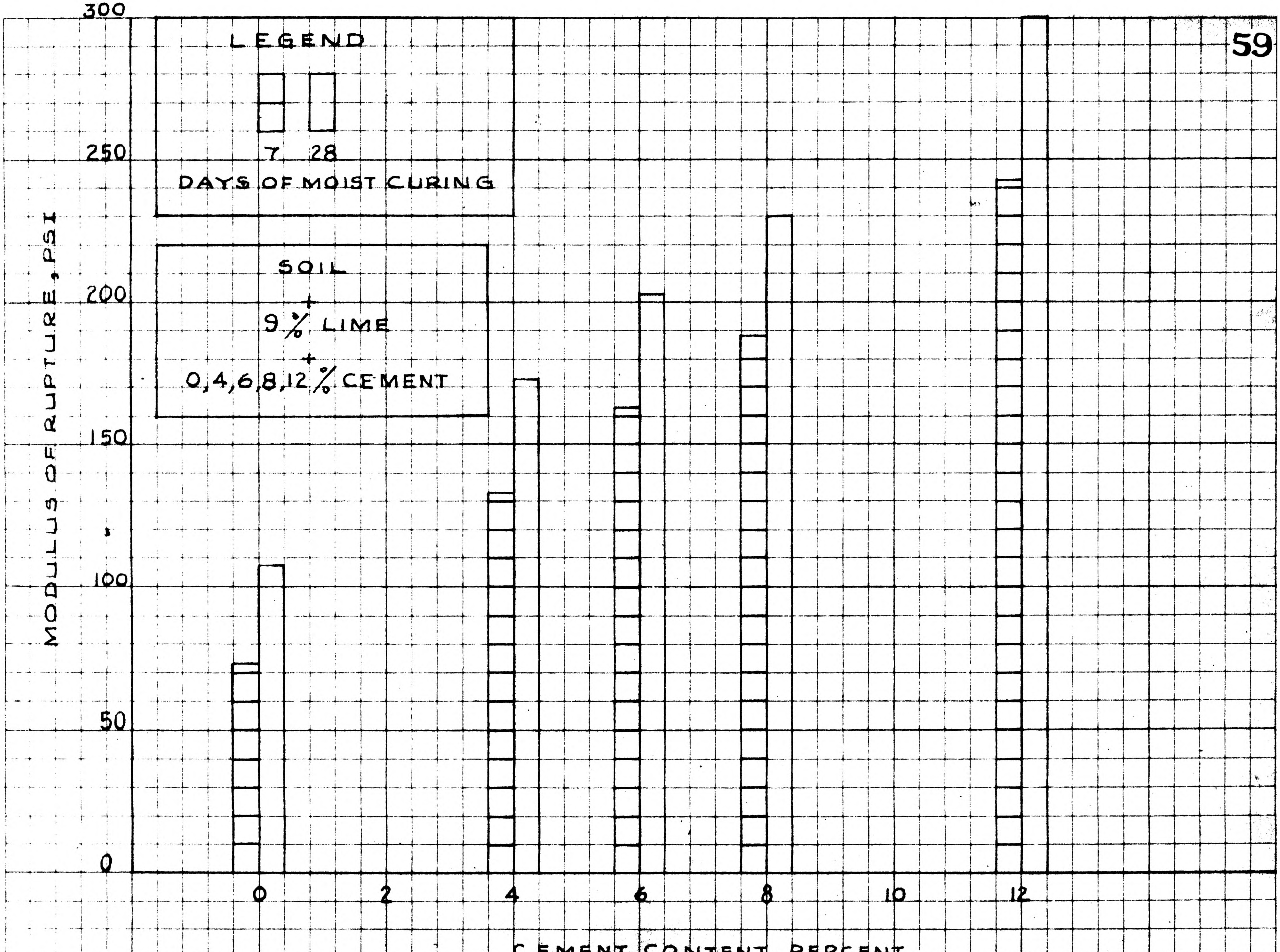
GRAPH NO. 1


LEGEND
7
28
DAYS OF MOIST CURING
SOIL
+
3 % LIME
+
0,4,6,8,12 % CEMENT
MODULUS OF RUPTURE, PSI
250
200
150
100
50
0
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

GRAPH NO. 2


LEGEND
7 28
DAYS OF MOIST CURING
SOIL
+
6% LIME
+
0,4,6,8,12% CEMENT
MODULUS OF RUPTURE, PSI
300
250
200
150
100
50
0
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

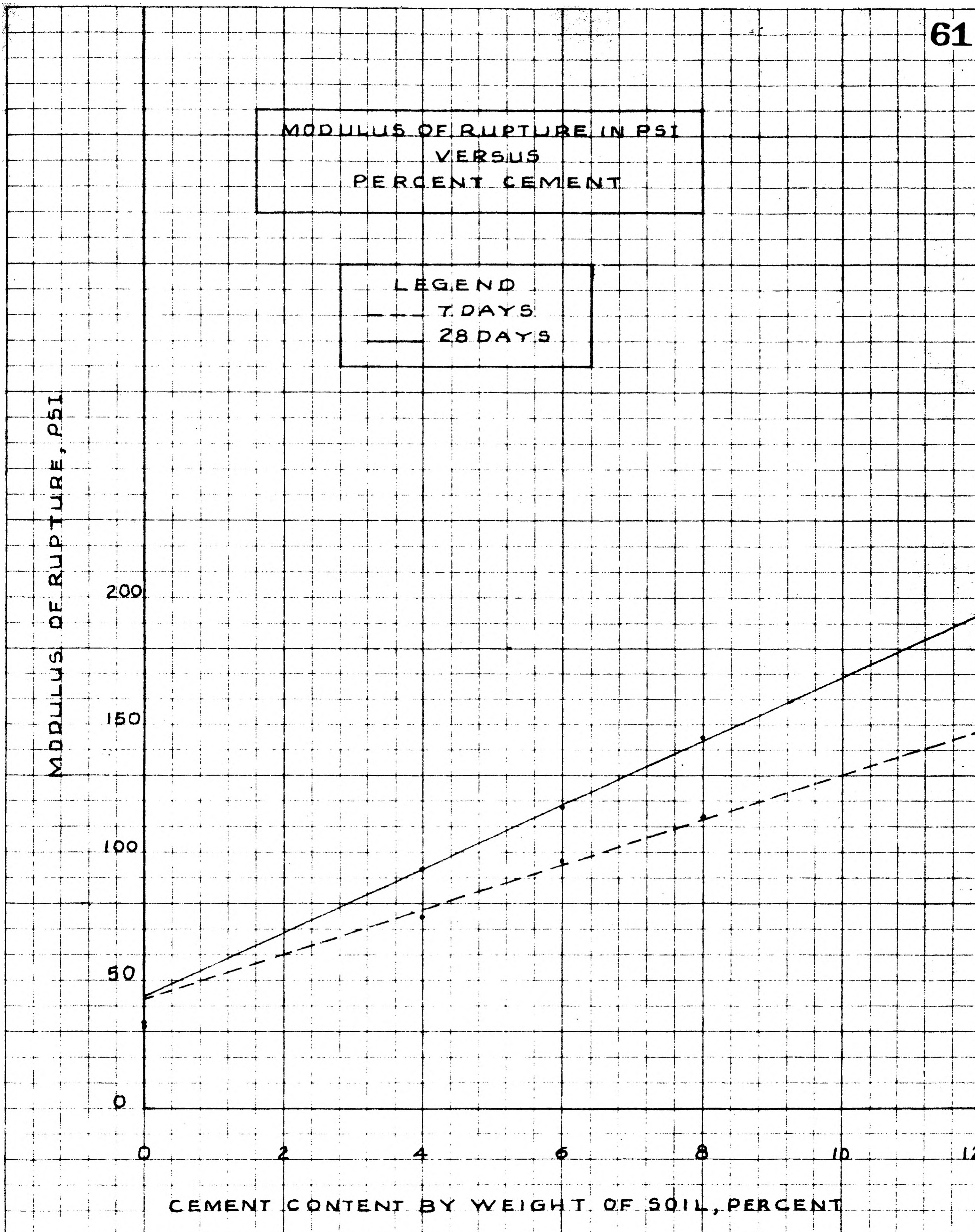
GRAPH NO. 3



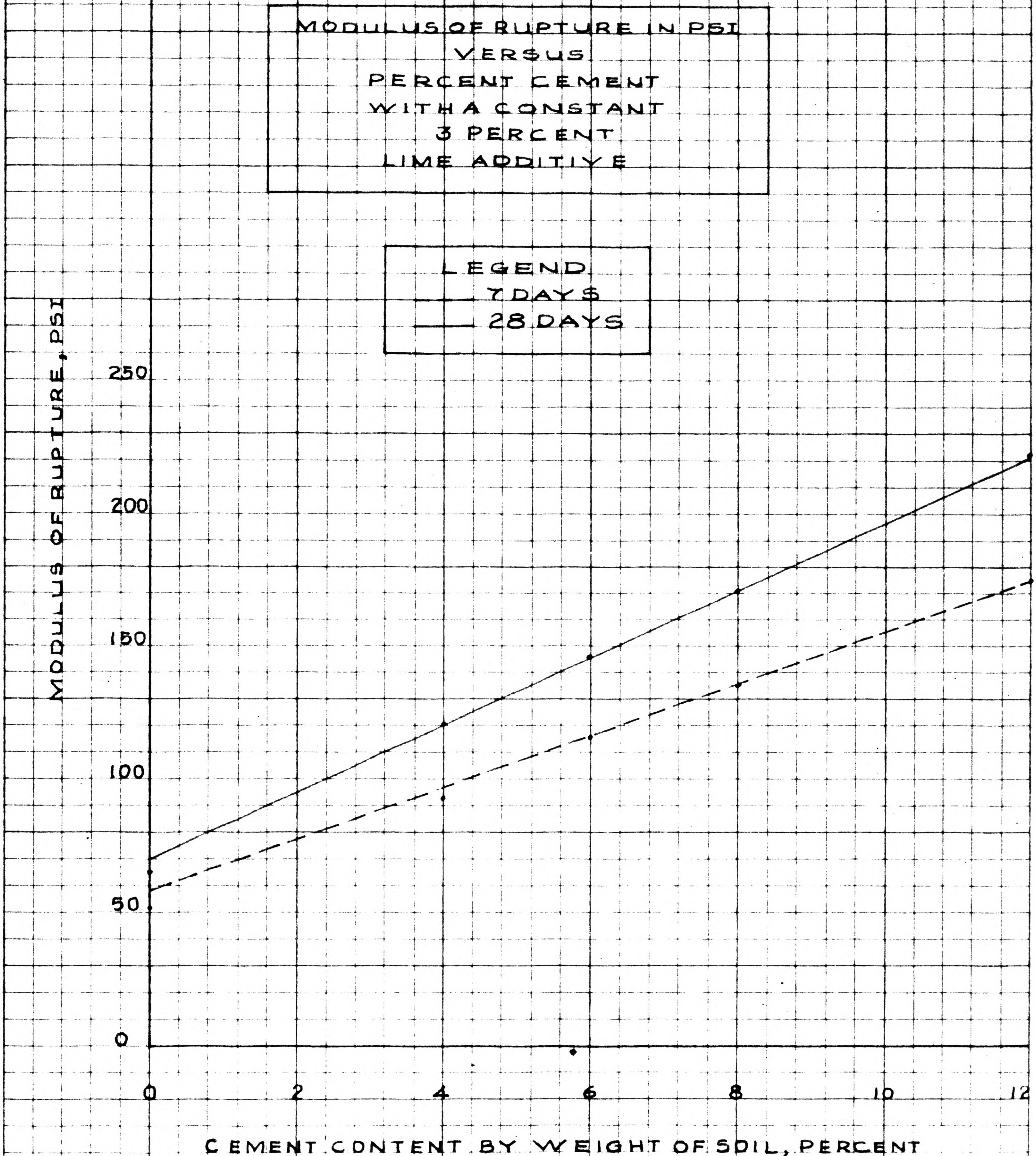
LEGEND
7
28
DAYS OF MOIST CURING
SOIL
+
9% LIME
+
0,4,6,8,12% CEMENT
MODULUS OF RUPTURE, PSI
300
250
200
150
100
50
0
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

GRAPH NO. 4

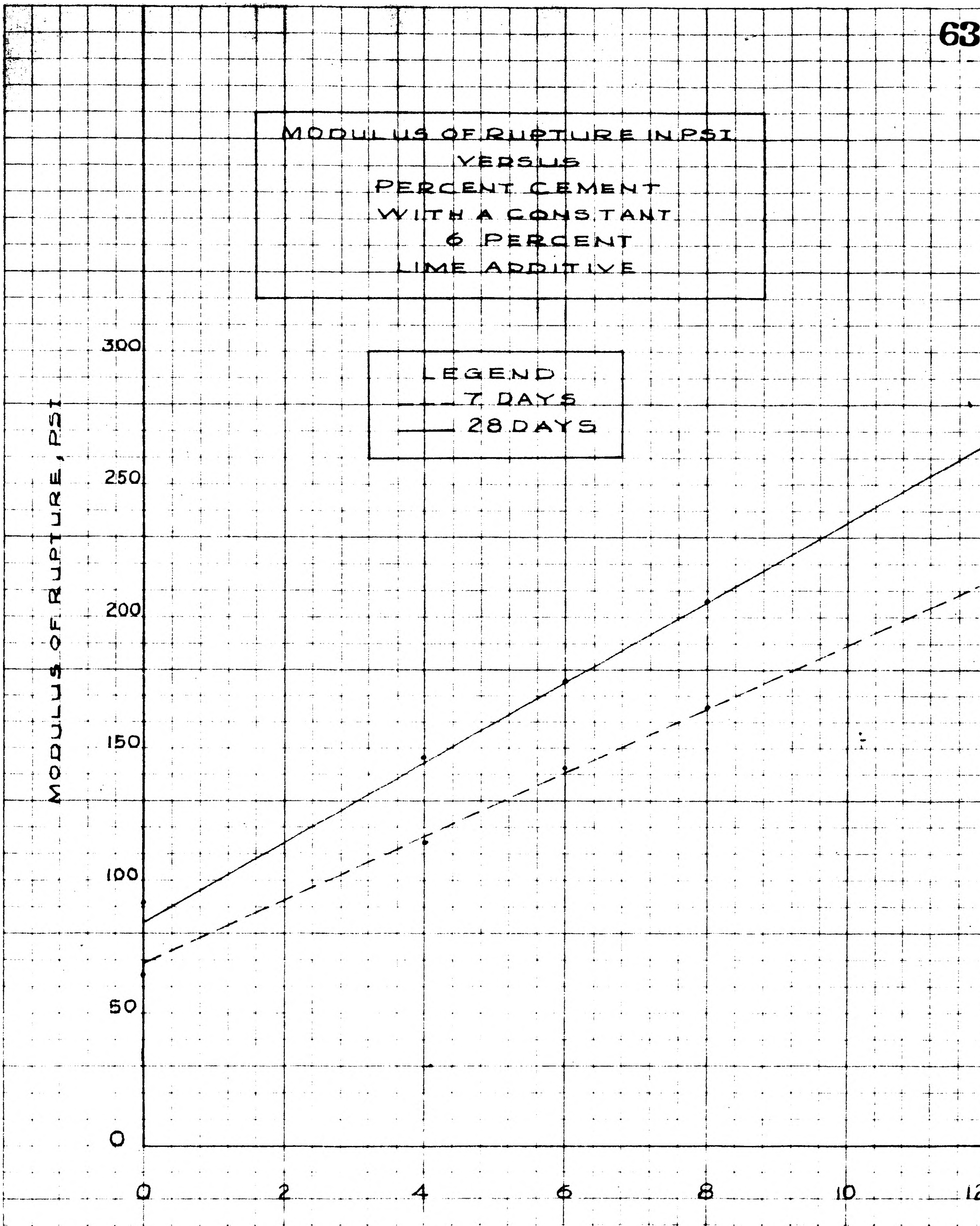
APPENDIX B
GRAPHS OF MODULUS OF RUPTURE TESTS


MODULUS OF RUPTURE IN PSI
VERSUS
PERCENT CEMENT
LEGEND
7 DAYS
28 DAYS
MODULUS OF RUPTURE, PSI
200
150
100
50
0
0
2
4
6
8
10
12
CEMENT CONTENT BY WEIGHT OF SOIL, PERCENT

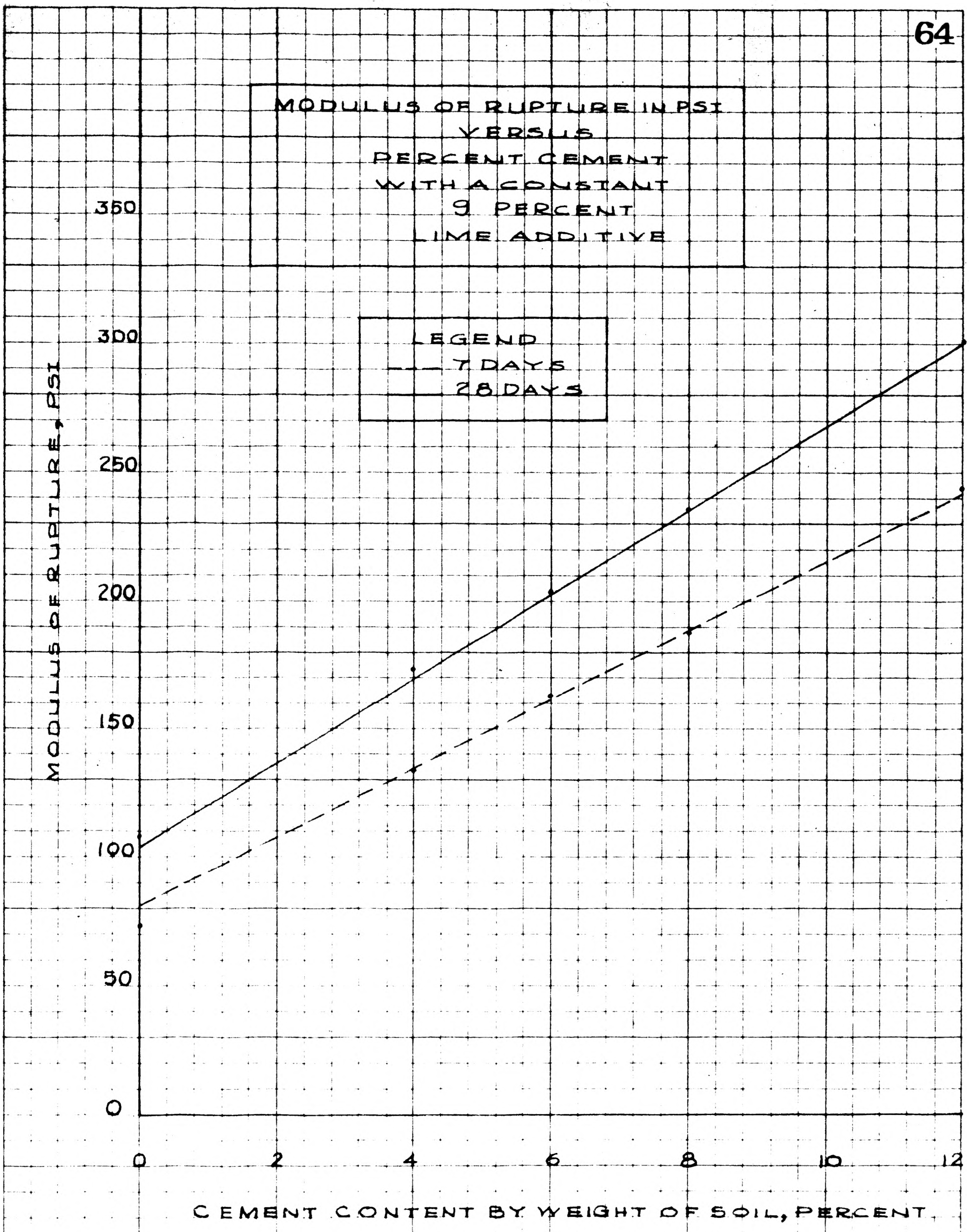
GRAPH NO. 5


MODULUS OF RUPTURE IN PSI
VERSUS
PERCENT CEMENT
WITH A CONSTANT
3 PERCENT
LIME ADDITIVE
LEGEND
7 DAYS
28 DAYS
MODULUS OF RUPTURE, PSI
250
200
150
100
50
0
0
2
4
6
8
10
12
CEMENT CONTENT BY WEIGHT OF SOIL, PERCENT

GRAPH NO. 6


MODULUS OF RUPTURE IN PSI
VERSUS
PERCENT CEMENT
WITH A CONSTANT
6 PERCENT
LIME ADDITIVE
LEGEND
7 DAYS
28 DAYS
MODULUS OF RUPTURE, PSI
0
50
100
150
200
250
300
0
2
4
6
8
10
12
CEMENT CONTENT BY WEIGHT OF SOIL, PERCENT

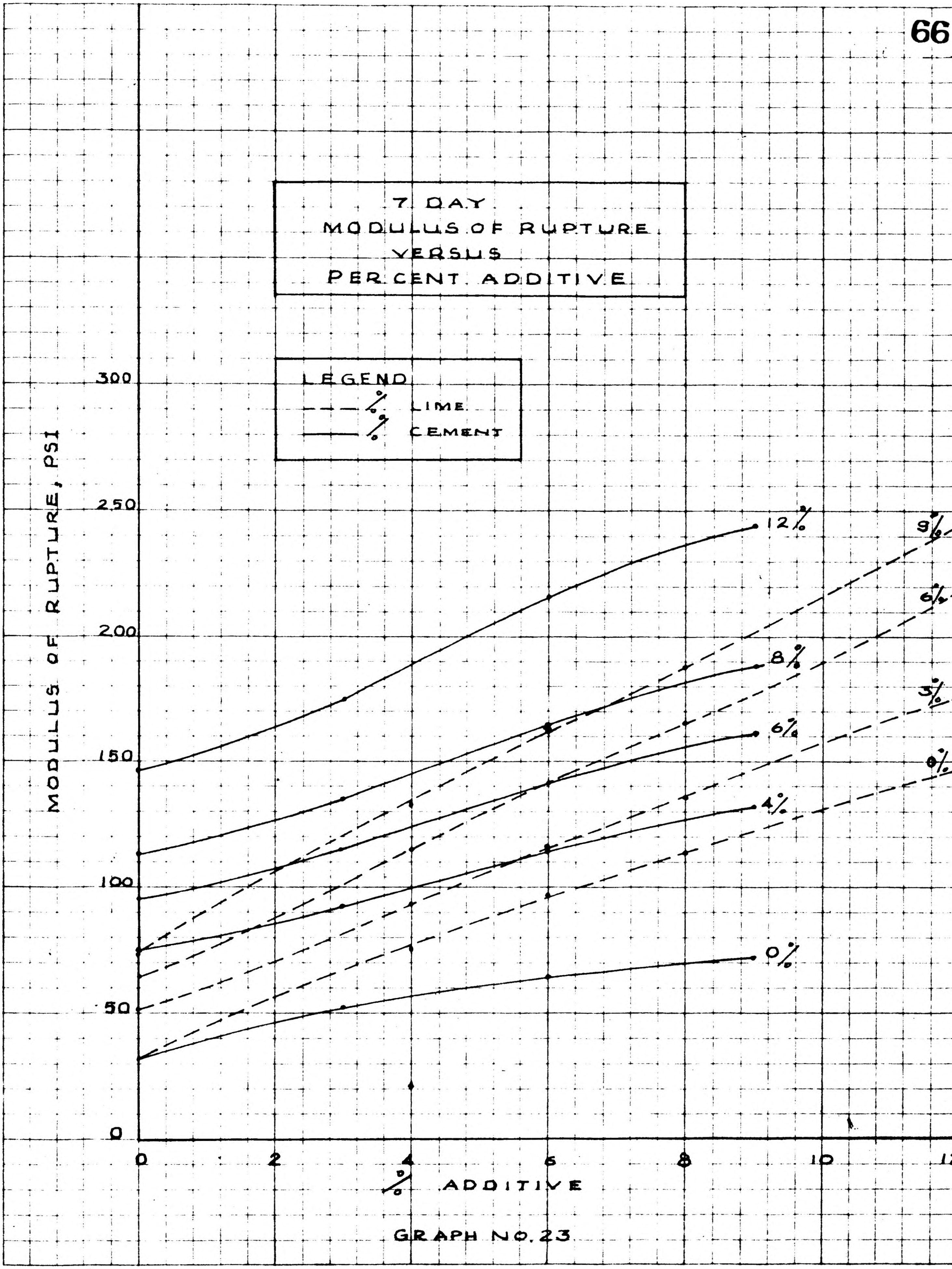
GRAPH NO. 7


MODULUS OF RUPTURE IN PSI
VERSUS
PERCENT CEMENT
WITH A CONSTANT
9 PERCENT
LIME ADDITIVE
LEGEND
7 DAYS
28 DAYS
MODULUS OF RUPTURE, PSI
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12
CEMENT CONTENT BY WEIGHT OF SOIL, PERCENT

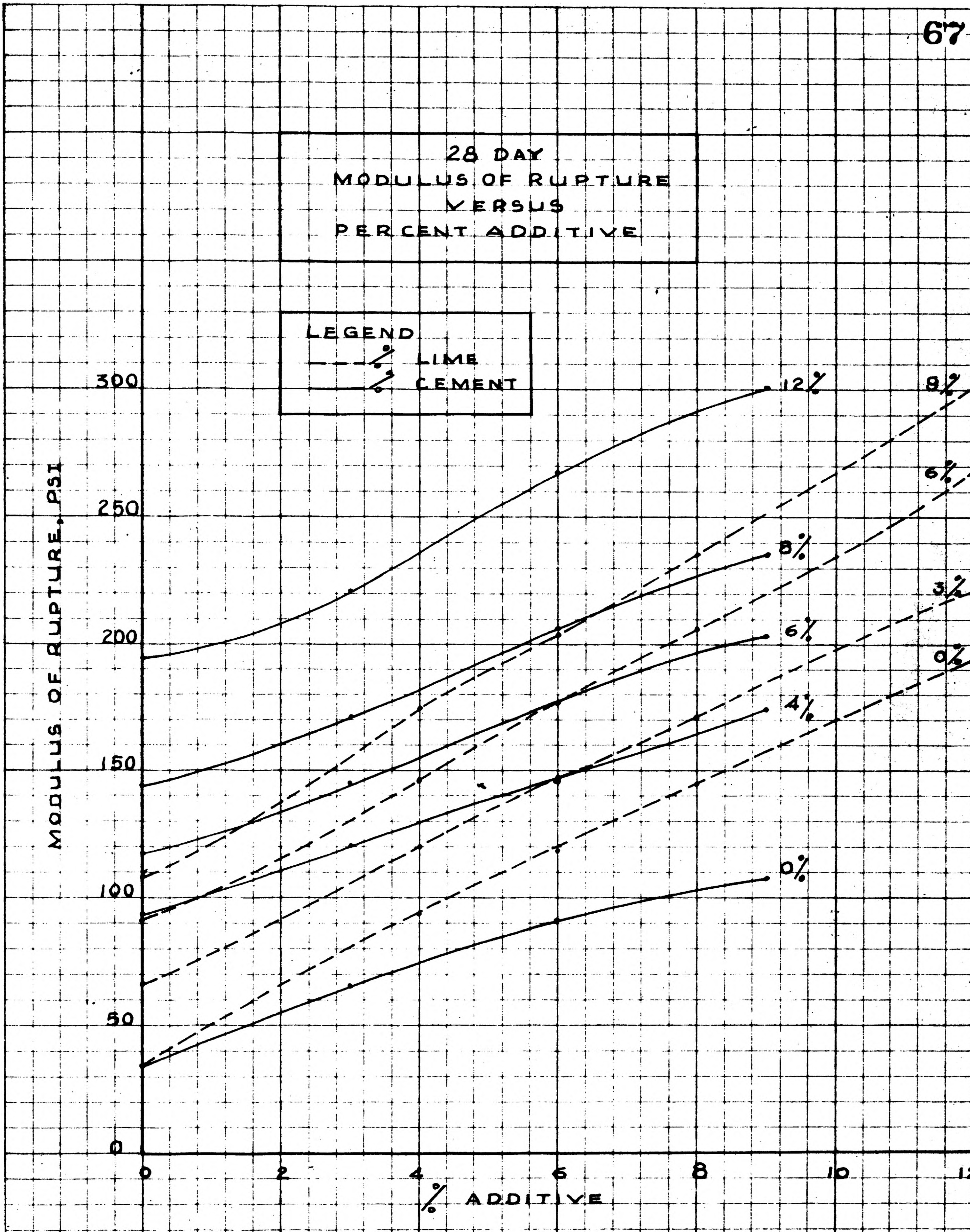
GRAPH NO. 8

APPENDIX C

7 AND 28 DAY MODULUS OF RUPTURE VERSUS PERCENT ADDITIVE

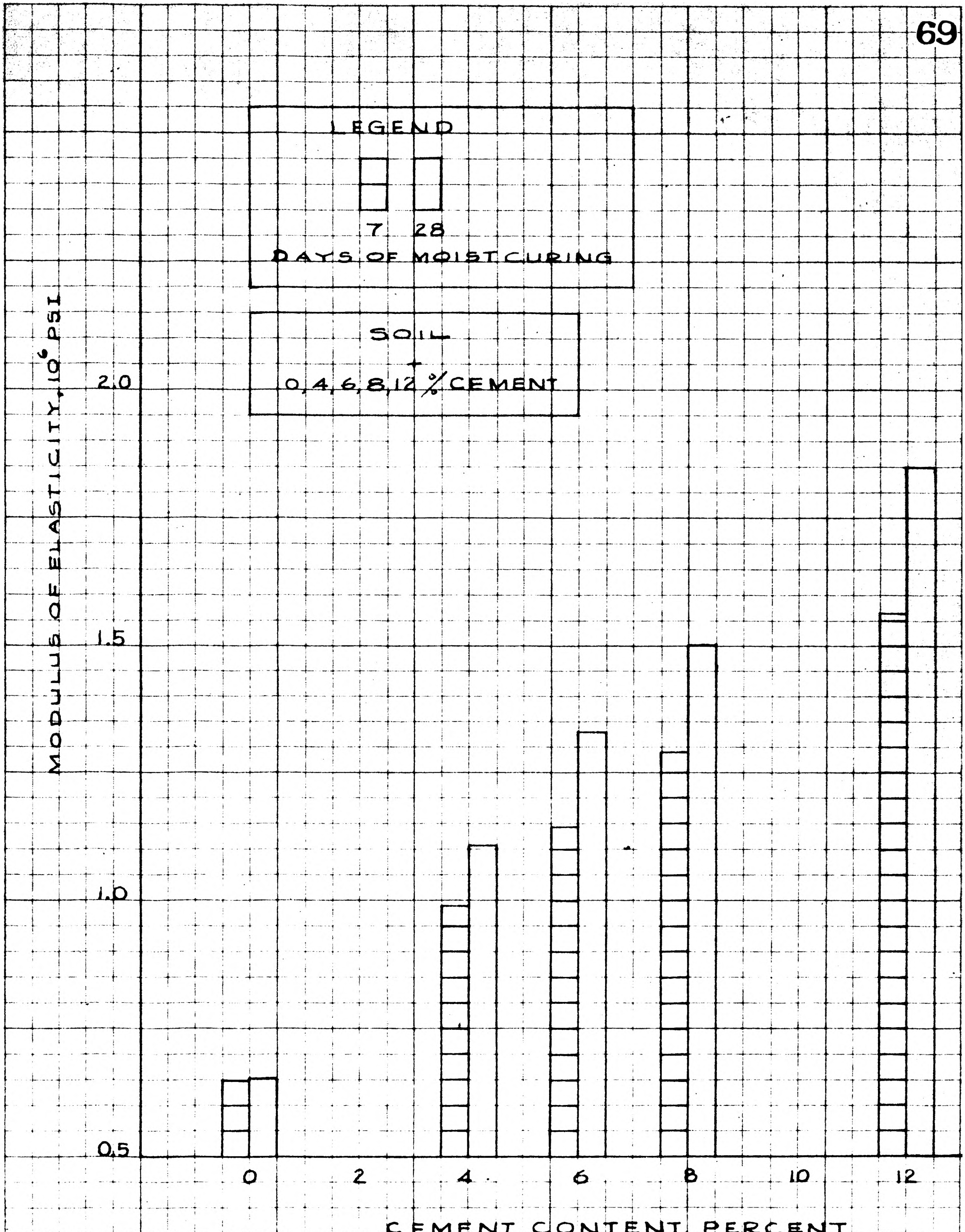

7 DAY
MODULUS OF RUPTURE
VERSUS
PER CENT ADDITIVE
LEGEND
% LIME
% CEMENT
MODULUS OF RUPTURE, PSI
0
50
100
150
200
250
300
0
2
4
6
8
10
12
% ADDITIVE
12%
8%
6%
4%
0%
9%
6%
3%
0%

GRAPH NO. 23

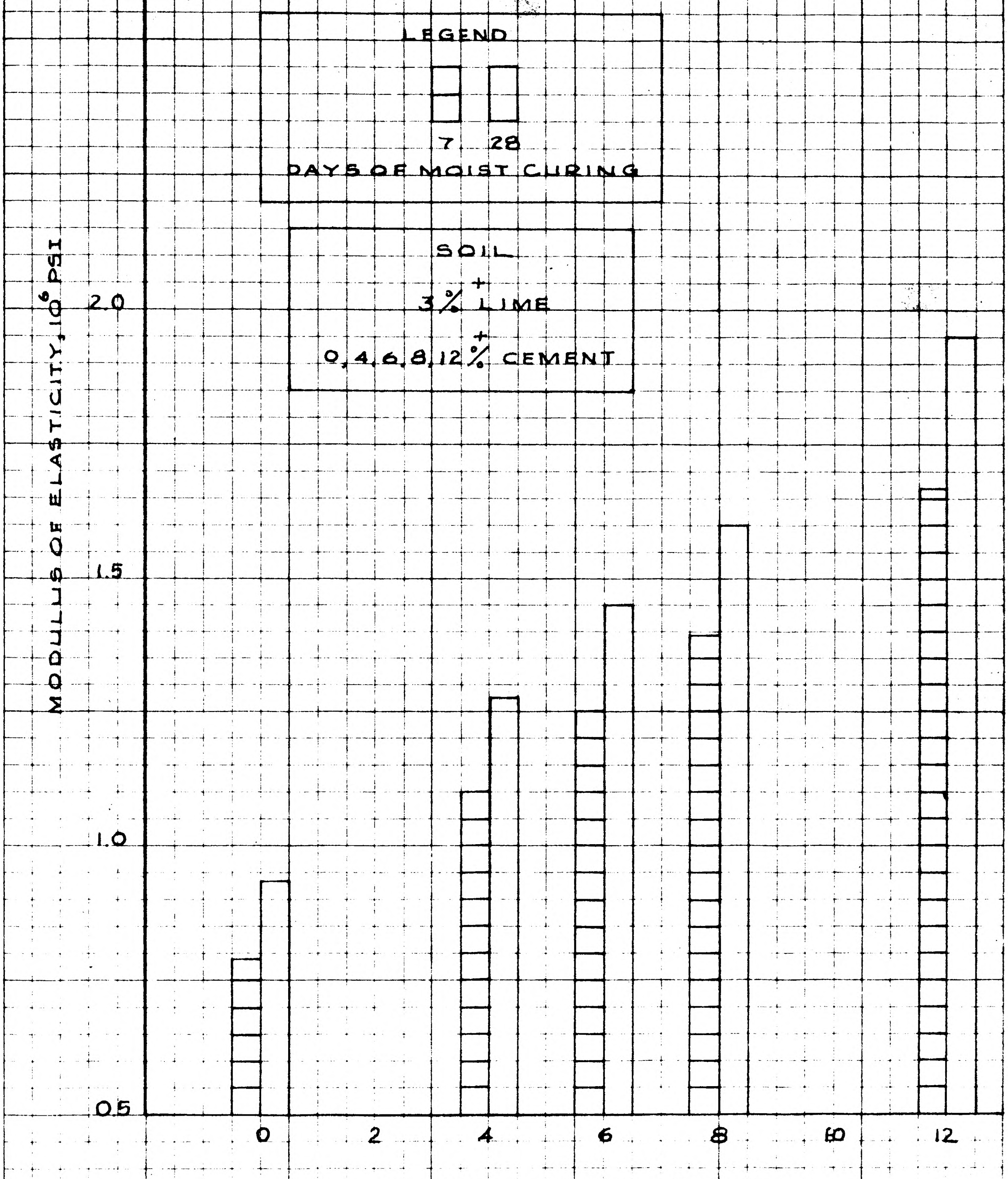

28 DAY
MODULUS OF RUPTURE
VERSUS
PERCENT ADDITIVE
LEGEND
% LIME
% CEMENT
MODULUS OF RUPTURE, PSI
0
50
100
150
200
250
300
0
2
4
6
8
10
12
% ADDITIVE
12%
8%
6%
4%
0%
8%
6%
3%
0%

GRAPH NO. 24

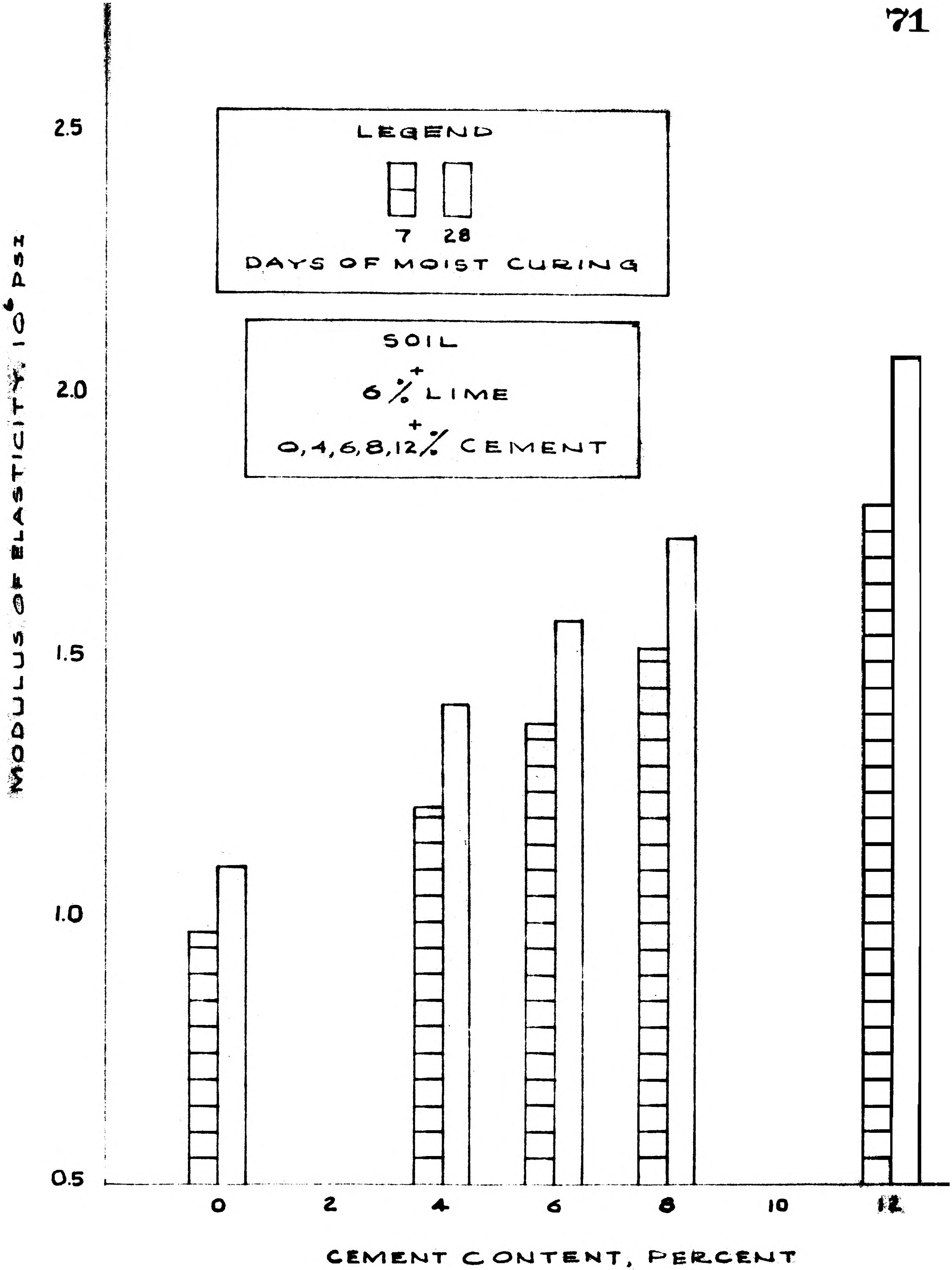
APPENDIX D
DATA OF MODULUS OF ELASTICITY TEST


LEGEND
7 28
DAYS OF MOIST CURING
SOIL
+
0,4,6,8,12 % CEMENT
MODULUS OF ELASTICITY, 10^6 PSI
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

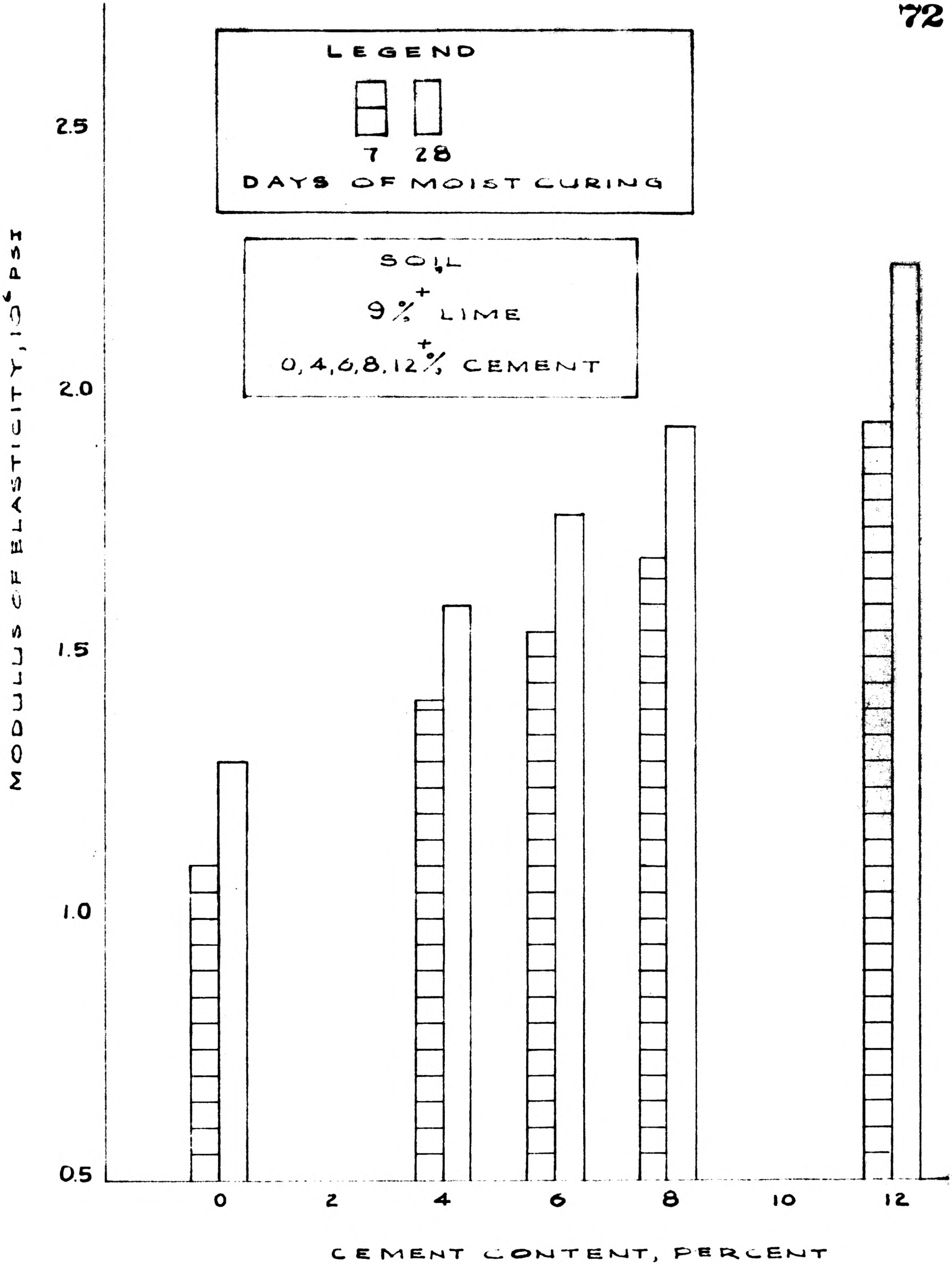
GRAPH NO. 9


LEGEND
7
28
DAYS OF MOIST CURING
SOIL
+
3% LIME
+
0,4,6,8,12% CEMENT
MODULUS OF ELASTICITY, 10^6 PSI
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

GRAPH NO. 10

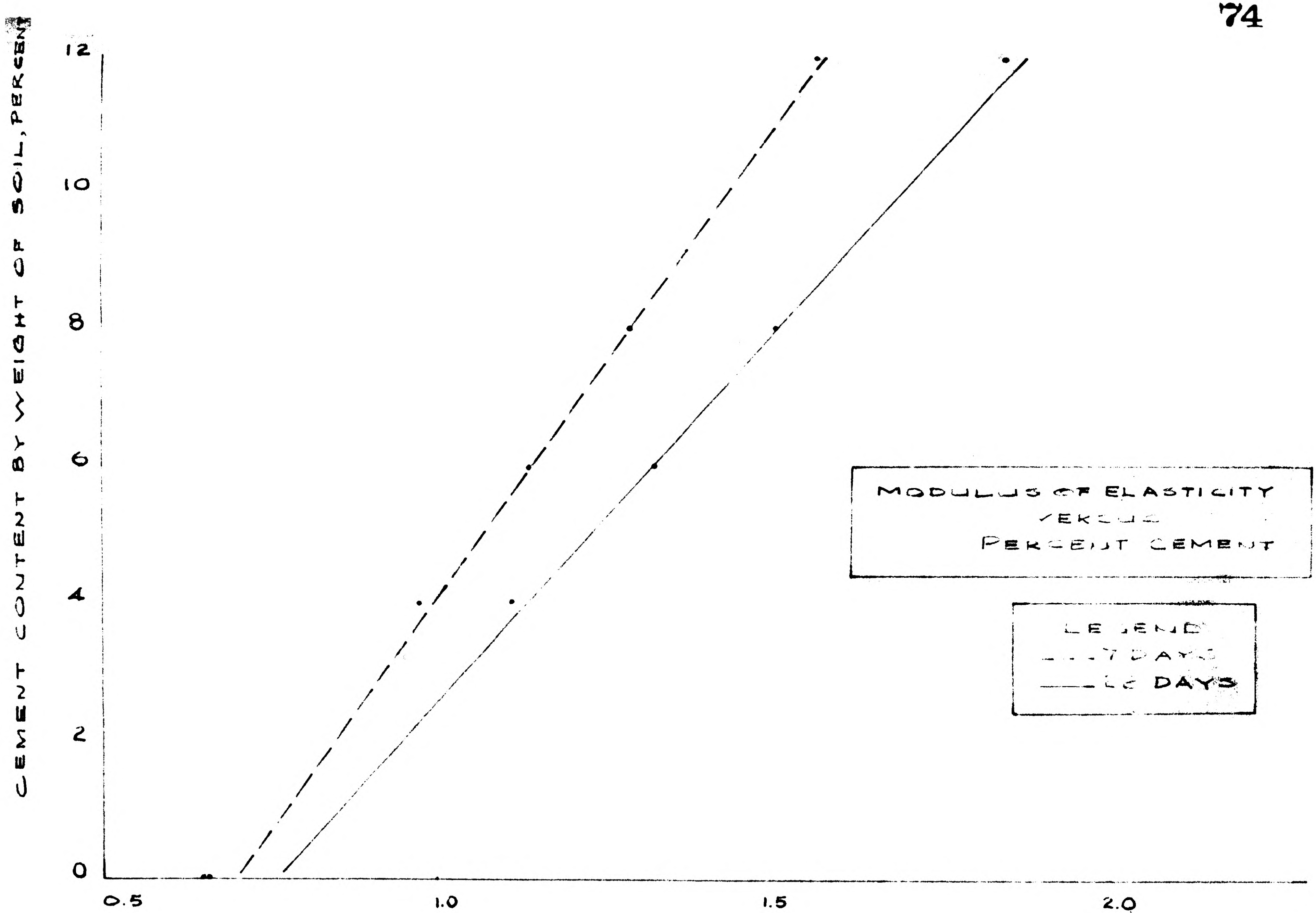

2.5
2.0
1.5
1.0
0.5
MODULUS OF ELASTICITY, 10^6 PSI
LEGEND
7
28
DAYS OF MOIST CURING
SOIL
+
6% LIME
+
0,4,6,8,12% CEMENT
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

GRAPH NO. 11


LEGEND
7
28
DAYS OF MOIST CURING
SOIL
+
9% LIME
+
0, 4, 6, 8, 12% CEMENT
MODULUS OF ELASTICITY, 10⁶ PSI
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
CEMENT CONTENT, PERCENT

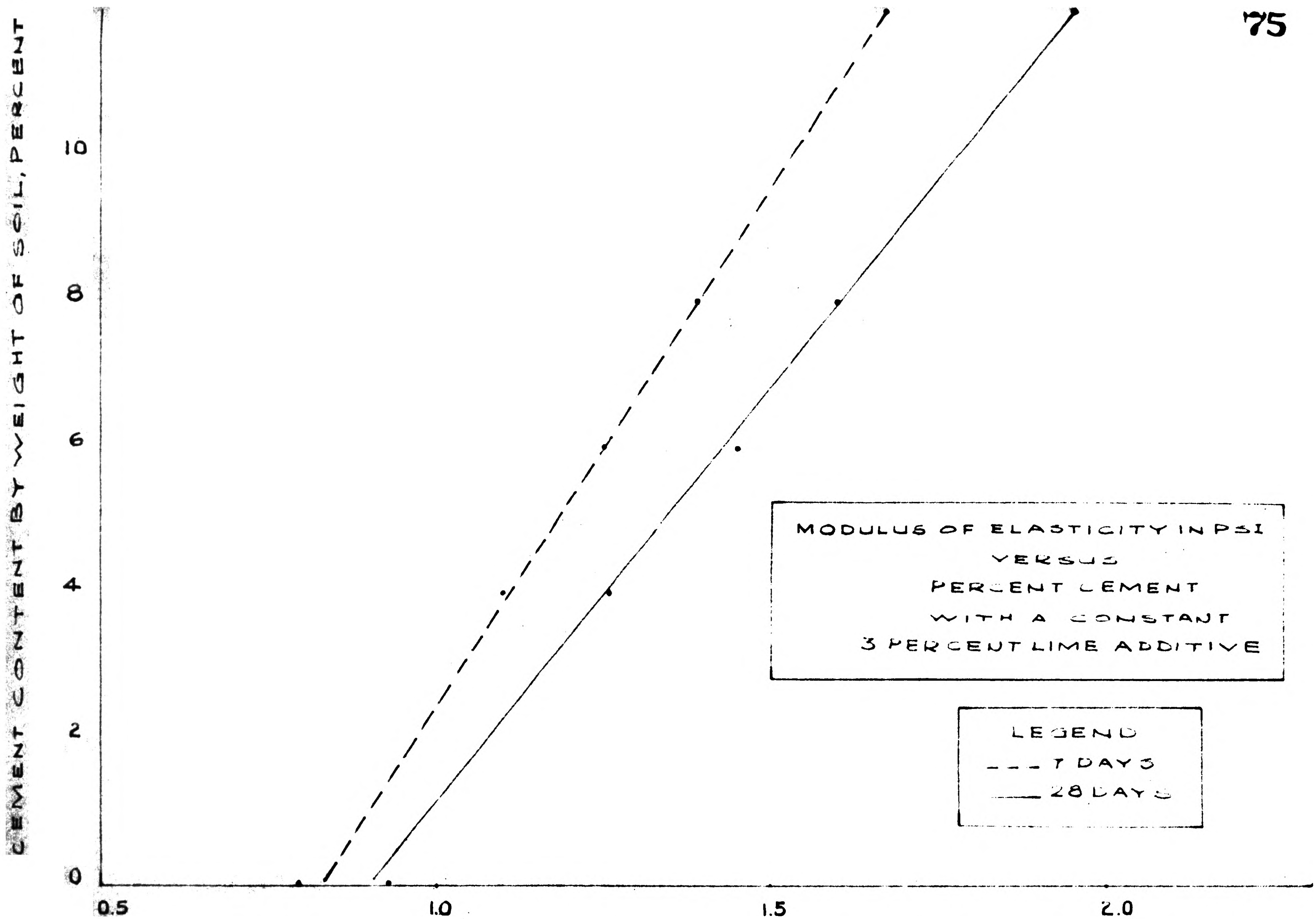
GRAPH NO. 12

APPENDIX E
GRAPHS OF MODULUS OF ELASTICITY TESTS



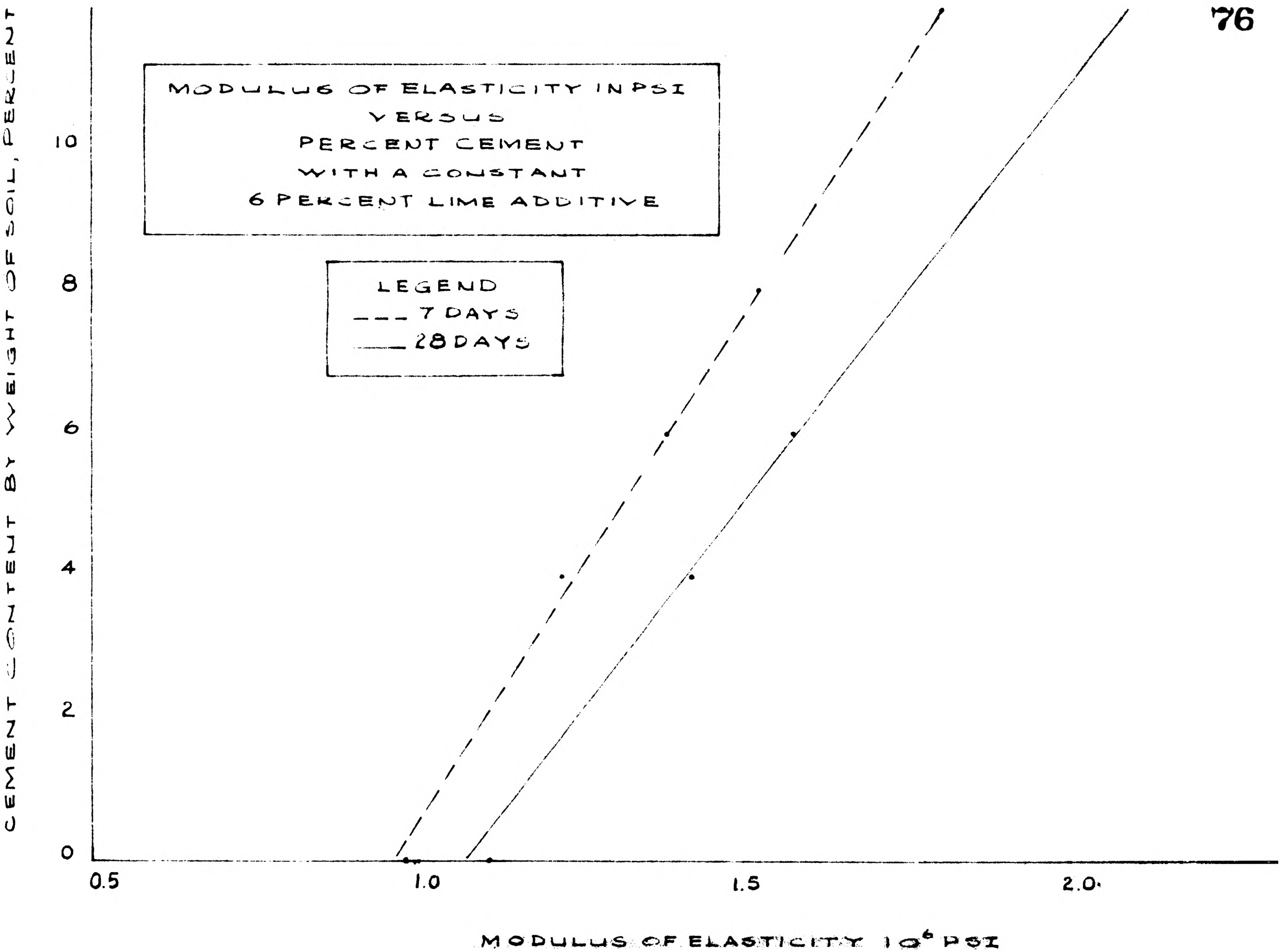
MODULUS OF ELASTICITY, 10^6 PSI

GRAPH NO. 13

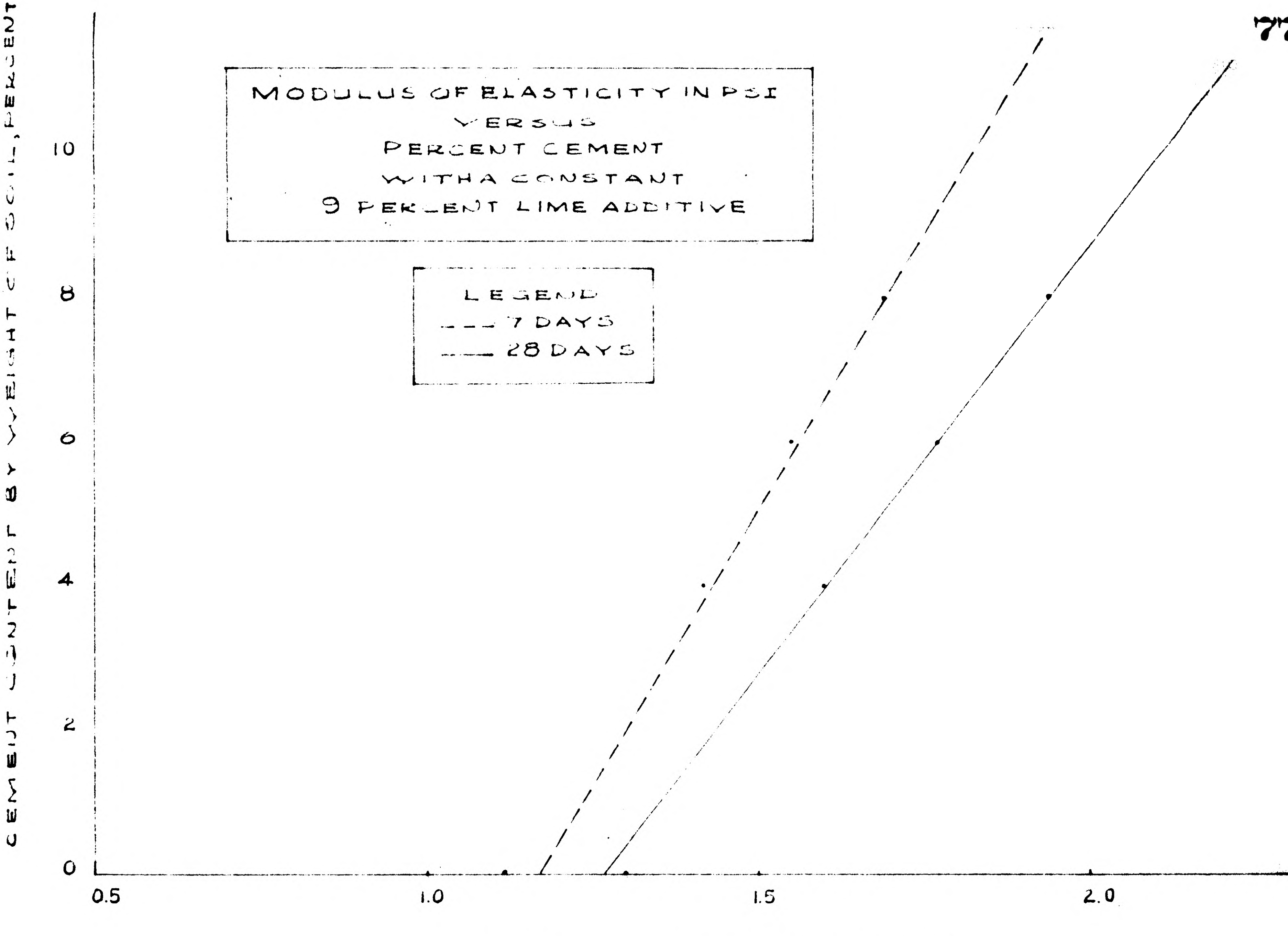


MODULUS OF ELASTICITY, 10^6 PSI

GRAPH NO. 14


MODULUS OF ELASTICITY IN PSI
VERSUS
PERCENT CEMENT
WITH A CONSTANT
6 PERCENT LIME ADDITIVE
LEGEND
7 DAYS
28 DAYS
CEMENT CONTENT BY WEIGHT OF SOIL, PERCENT
0
2
4
6
8
10
0.5
1.0
1.5
2.0
MODULUS OF ELASTICITY 10^6 PSI

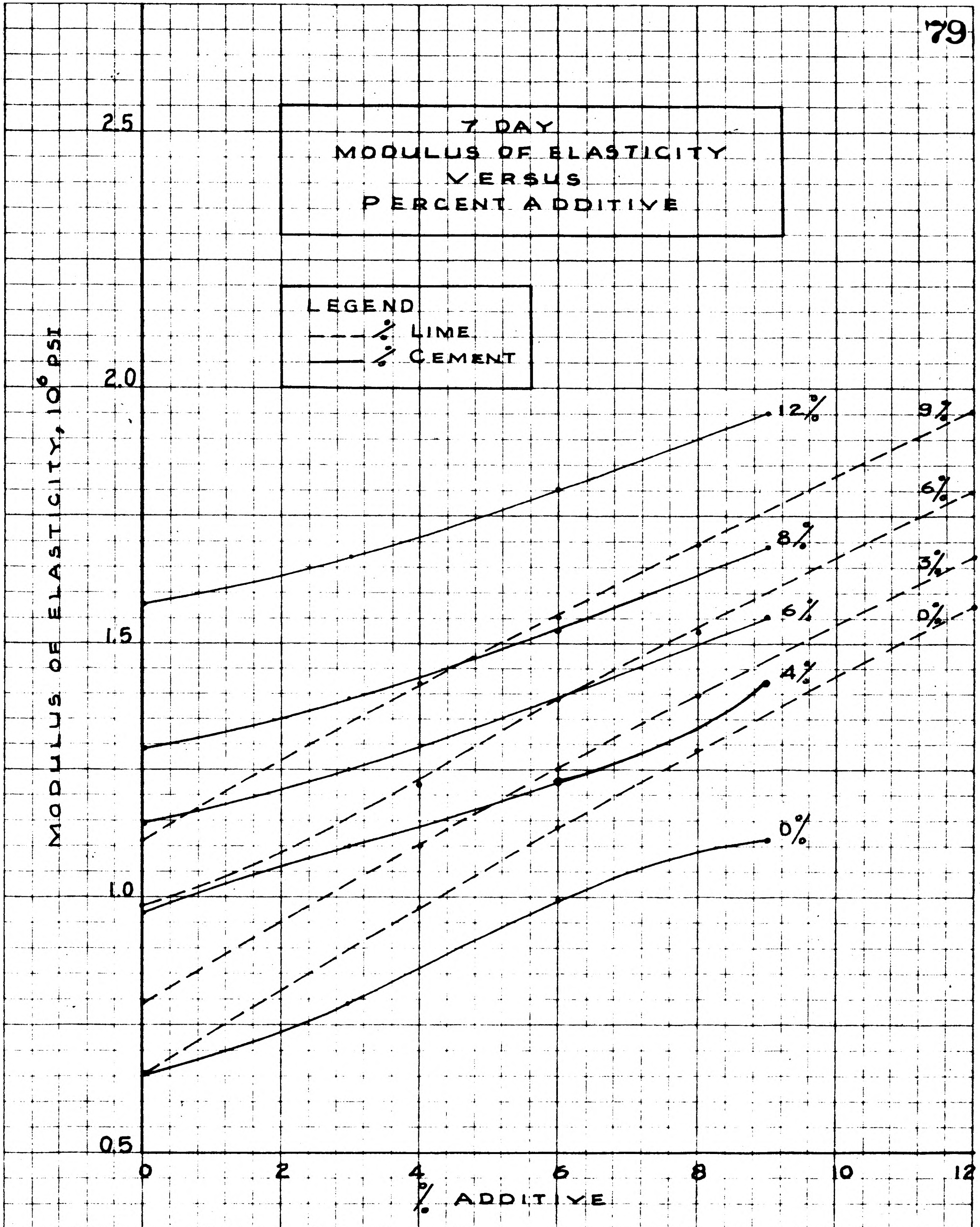
GRAPH NO. 15


MODULUS OF ELASTICITY IN PSI
VERSUS
PERCENT CEMENT
WITH A CONSTANT
9 PERCENT LIME ADDITIVE
LEGEND
7 DAYS
28 DAYS
CEMENT CONTENT BY WEIGHT OF SOIL, PERCENT
0
2
4
6
8
10
0.5
1.0
1.5
2.0
MODULUS OF ELASTICITY, 10^6 PSI

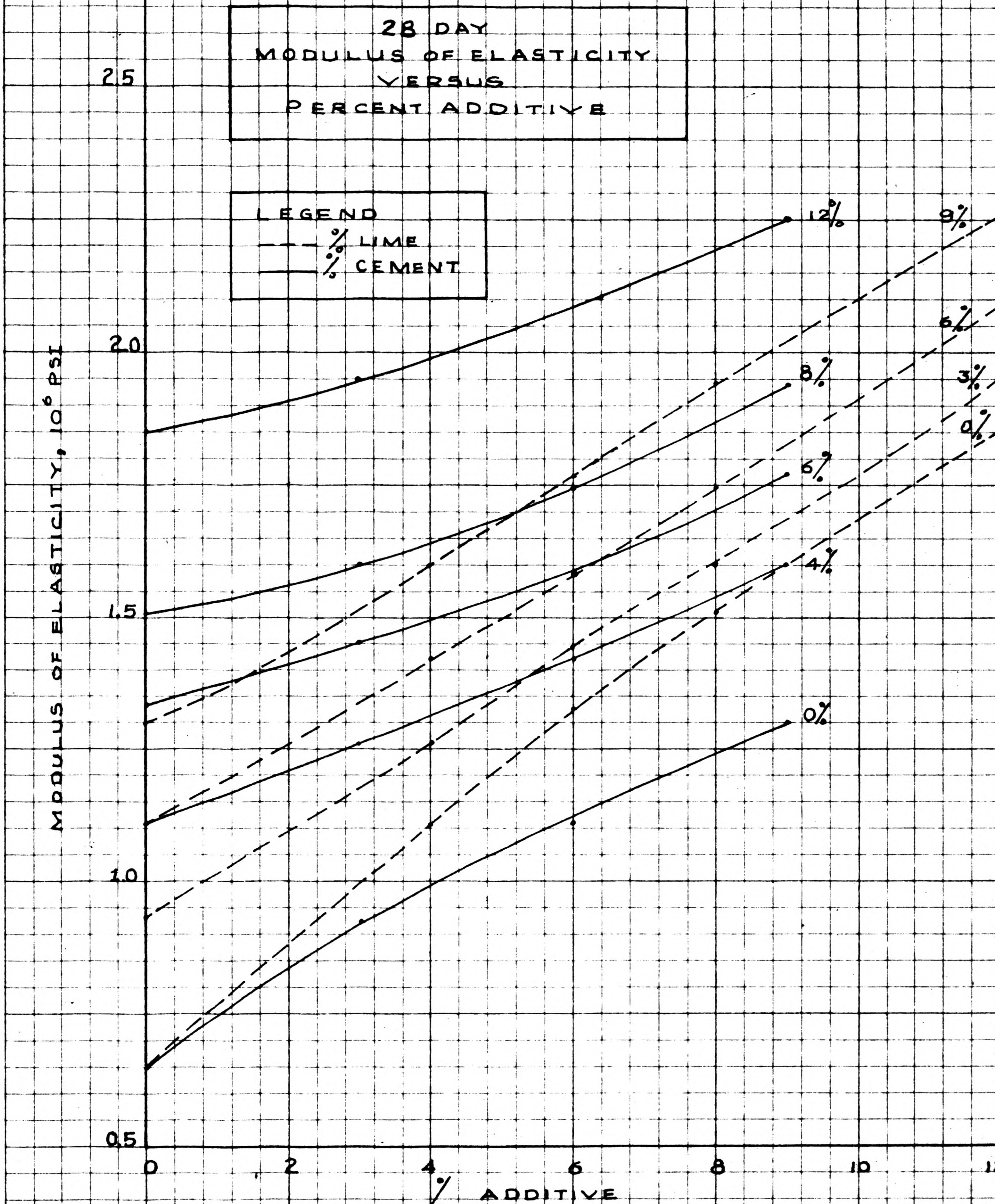
GRAPH NO. 16

APPENDIX F

7 AND 28 DAY MODULUS OF ELASTICITY VERSUS PERCENT ADDITIVE


7 DAY
MODULUS OF ELASTICITY
VERSUS
PERCENT ADDITIVE
LEGEND
% LIME
% CEMENT
MODULUS OF ELASTICITY, 10^6 PSI
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
% ADDITIVE
12%
8%
6%
4%
0%
9%
6%
3%
0%

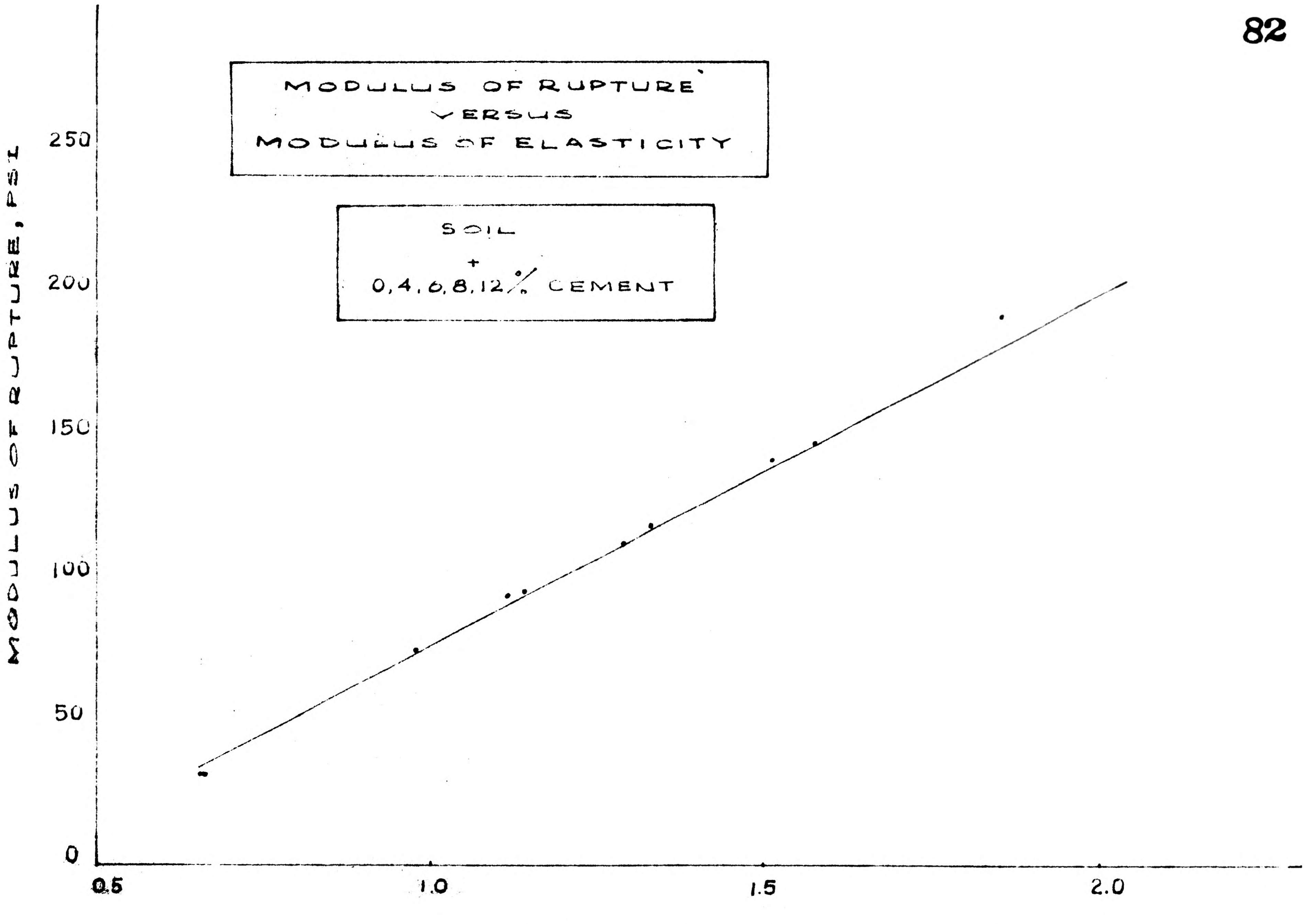
GRAPH NO. 25


28 DAY
MODULUS OF ELASTICITY
VERSUS
PERCENT ADDITIVE
LEGEND
% LIME
% CEMENT
12%
9%
6%
8%
3%
0%
6%
4%
0%
2.5
2.0
1.5
1.0
0.5
MODULUS OF ELASTICITY, 10^6 PSI
0
2
4
6
8
10
12
% ADDITIVE

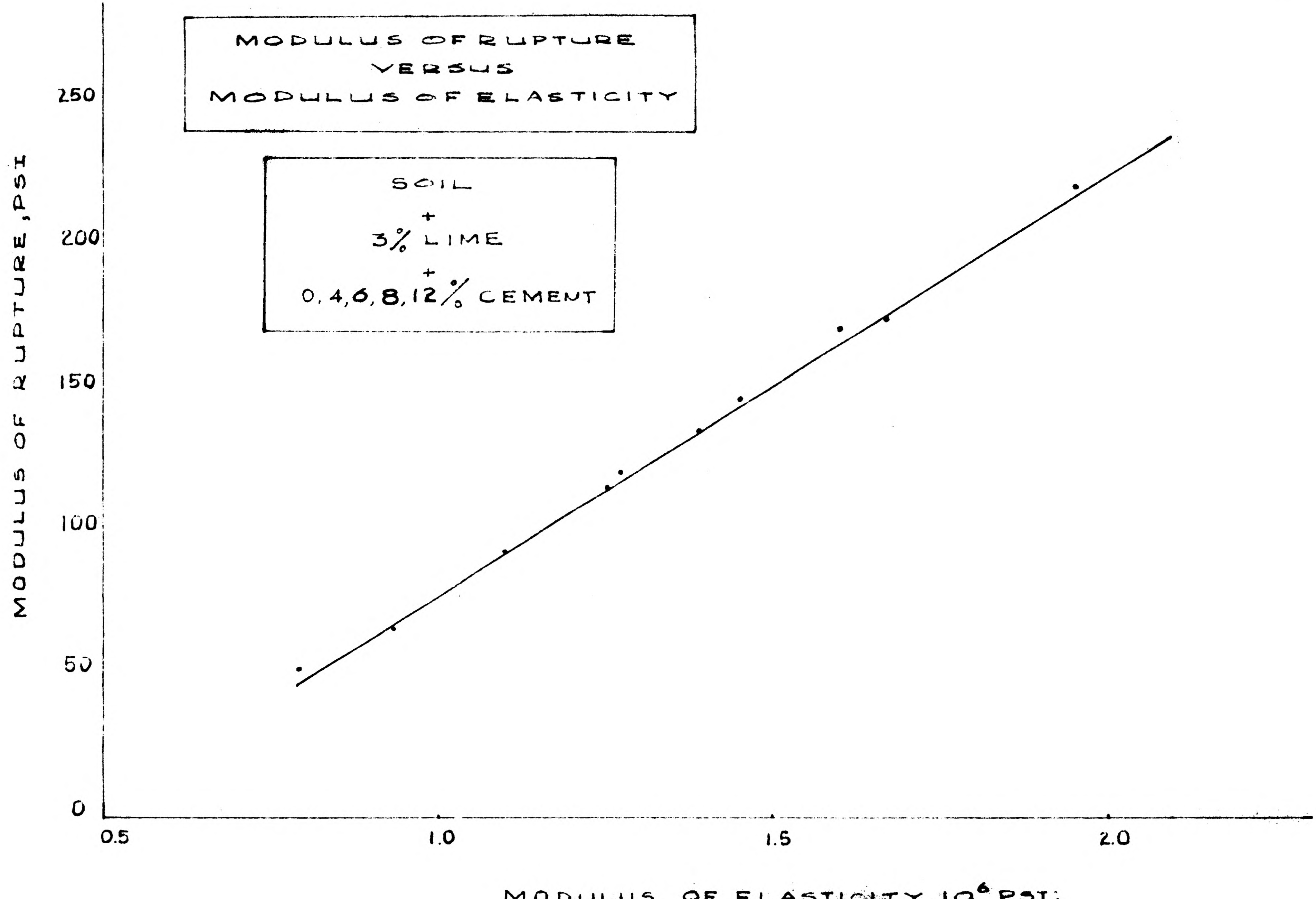
GRAPH NO. 26

APPENDIX G

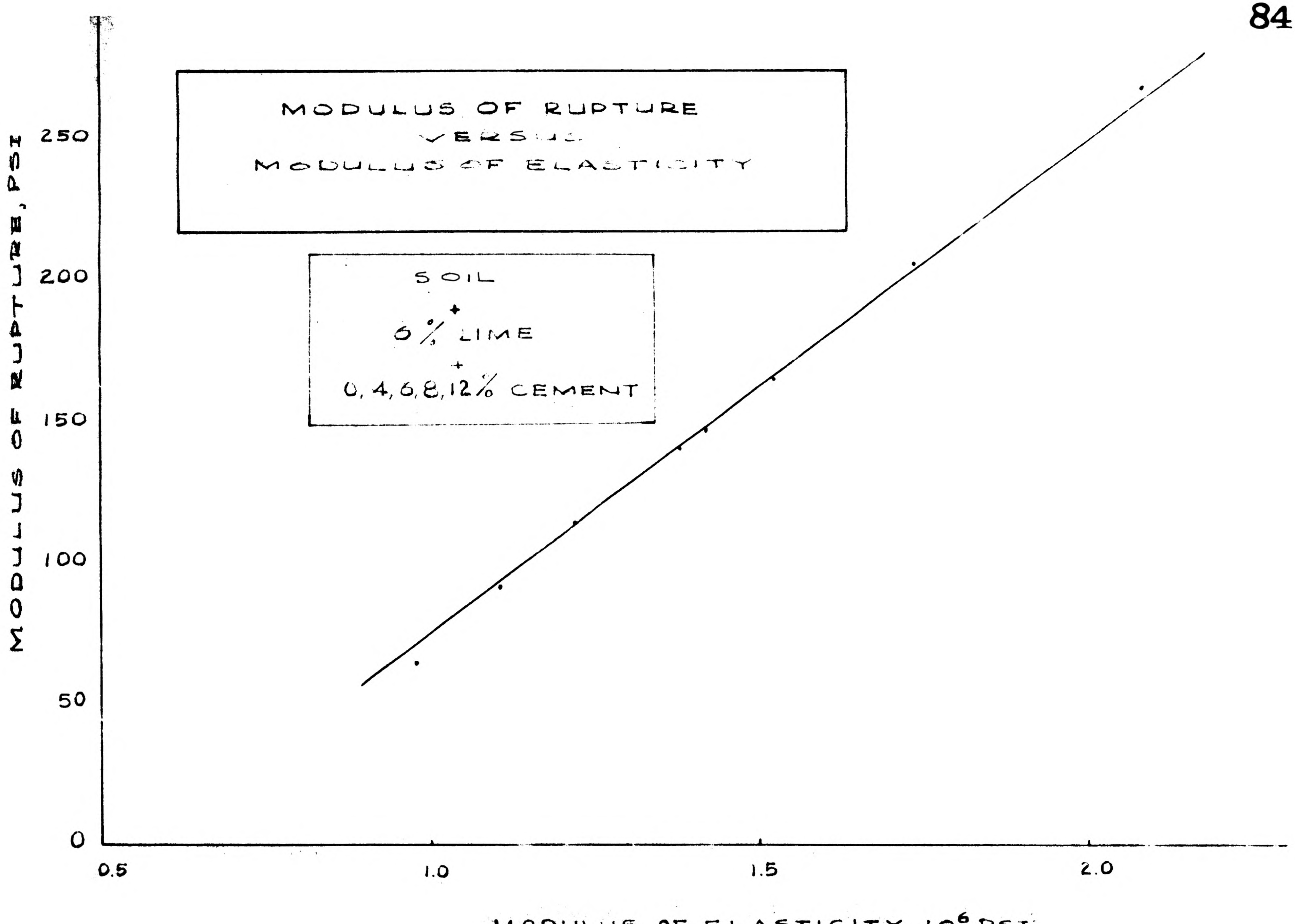
GRAPHS OF MODULUS OF RUPTURE VERSUS MODULUS OF ELASTICITY


MODULUS OF RUPTURE
VERSUS
MODULUS OF ELASTICITY
SOIL
+
0, 4, 6, 8, 12 % CEMENT
MODULUS OF RUPTURE, PSI
0
50
100
150
200
250
0.5
1.0
1.5
2.0
MODULUS OF ELASTICITY, 10⁶ PSI

GRAPH NO. 17

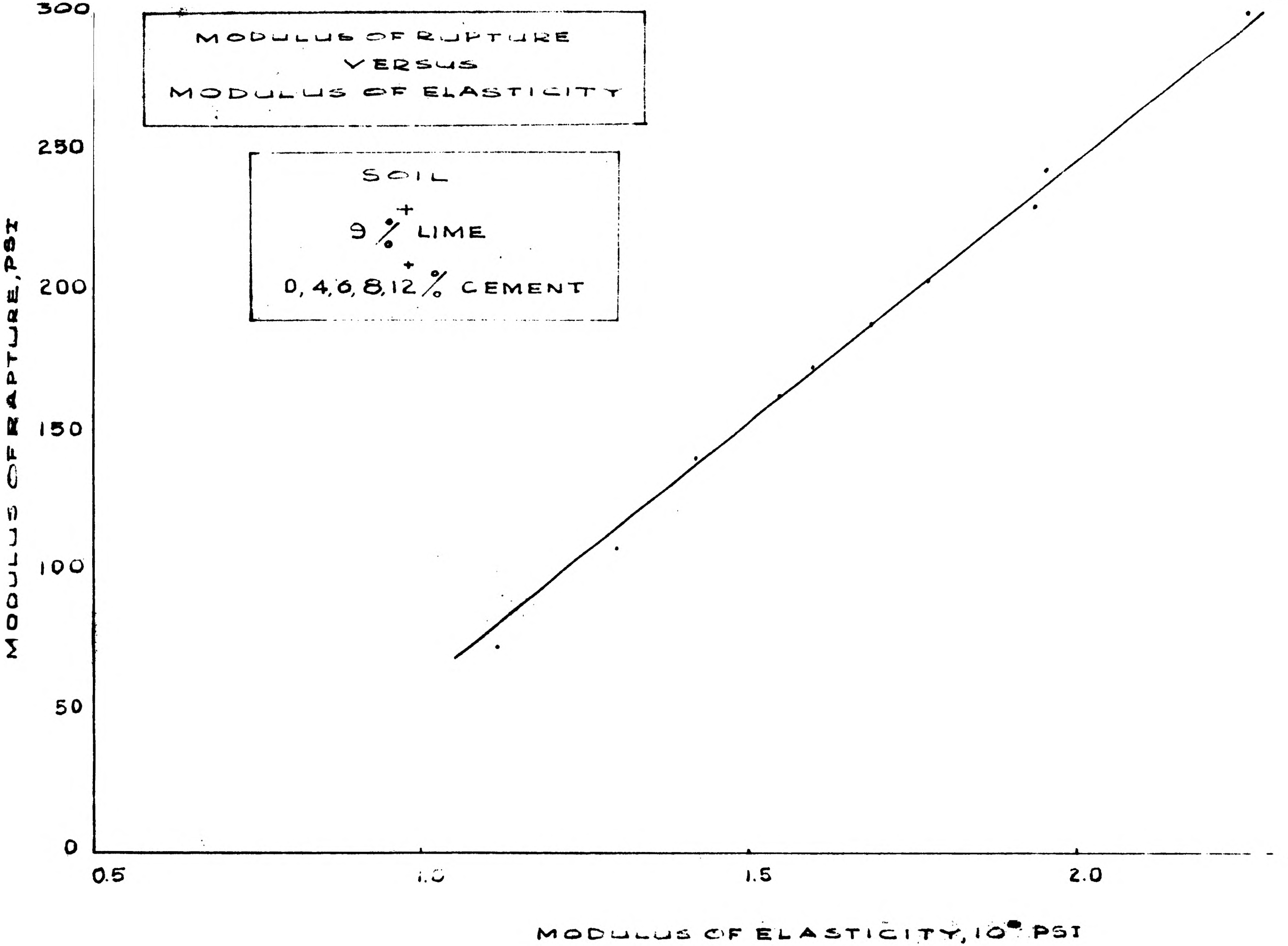

MODULUS OF RUPTURE
VERSUS
MODULUS OF ELASTICITY
SOIL
+
3% LIME
+
0, 4, 6, 8, 12% CEMENT
MODULUS OF RUPTURE, PSI
0
50
100
150
200
250
0.5
1.0
1.5
2.0
MODULUS OF ELASTICITY, 10^6 PSI

GRAPH NO. 18



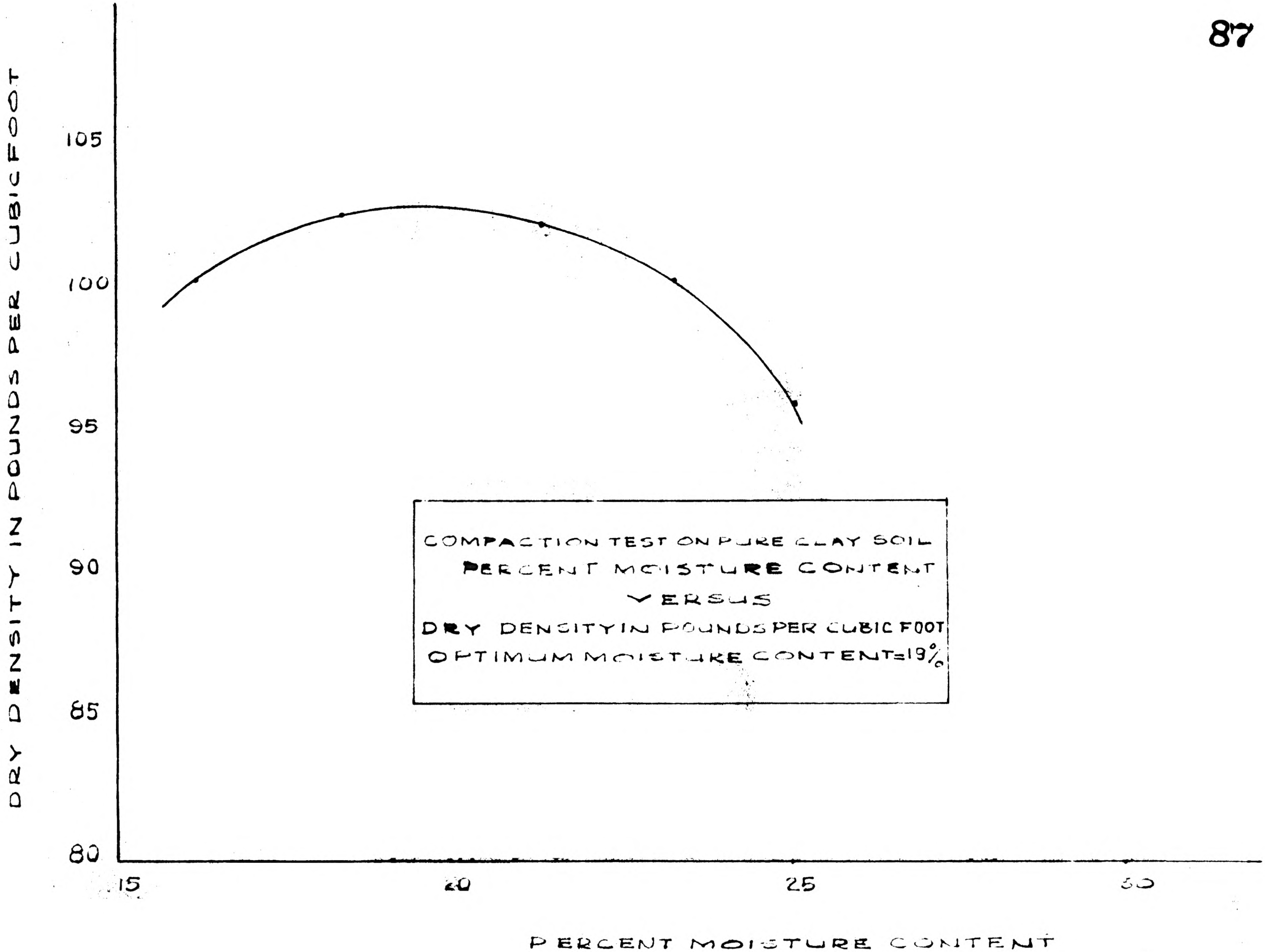
MODULUS OF RUPTURE
VERSUS
MODULUS OF ELASTICITY
SOIL
+
6% LIME
+
0, 4, 6, 8, 12% CEMENT
MODULUS OF RUPTURE, PSI
0
50
100
150
200
250
0.5
1.0
1.5
2.0
MODULUS OF ELASTICITY, 10^6 PSI

GRAPH NO. 19

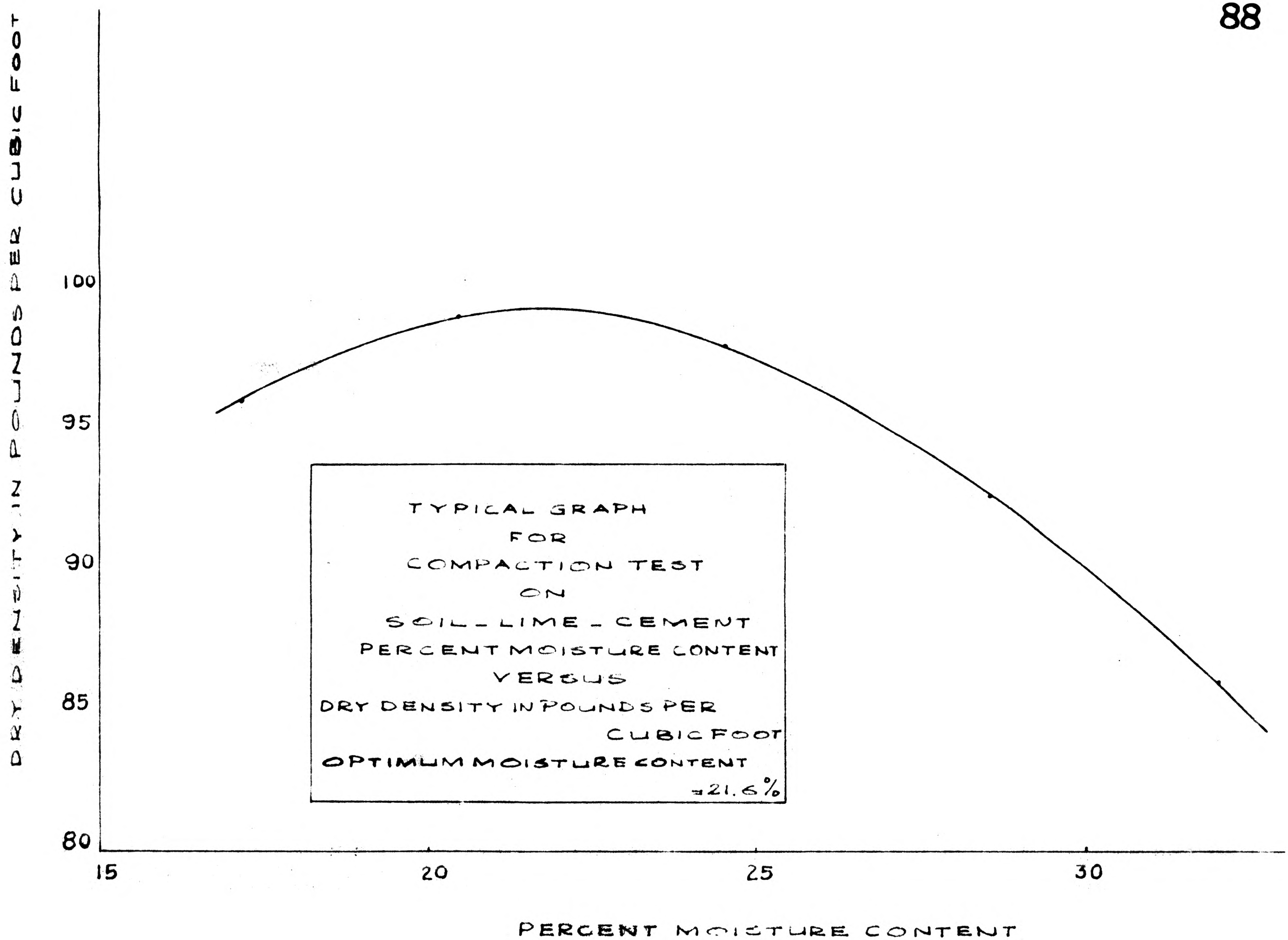

MODULUS OF RUPTURE
VERSUS
MODULUS OF ELASTICITY
SOIL
+
9% LIME
+
0, 4, 6, 8, 12 % CEMENT
MODULUS OF RAPTURE, PSI
300
250
200
150
100
50
0
0.5
1.0
1.5
2.0
MODULUS OF ELASTICITY, 10⁶ PSI

GRAPH NO. 20

APPENDIX H
TYPICAL MOISTURE-DENSITY RELATIONS GRAPHS


DRY DENSITY IN POUNDS PER CUBIC FOOT
105
100
95
90
85
80
15
20
25
30
COMPACTION TEST ON PURE CLAY SOIL
PERCENT MOISTURE CONTENT
VERSUS
DRY DENSITY IN POUNDS PER CUBIC FOOT
OPTIMUM MOISTURE CONTENT=19%
PERCENT MOISTURE CONTENT

GRAPH NO. 21


DRY DENSITY IN POUNDS PER CUBIC FOOT
100
95
90
85
80
15
20
25
30
TYPICAL GRAPH
FOR
COMPACTION TEST
ON
SOIL - LIME - CEMENT
PERCENT MOISTURE CONTENT
VERSUS
DRY DENSITY IN POUNDS PER
CUBIC FOOT
OPTIMUM MOISTURE CONTENT
=21.6%
PERCENT MOISTURE CONTENT

GRAPH NO. 22

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VITA

Ismail Yolar was born on January 25, 1934 in Istanbul, Turkey. After completing his primary and high school education in Turkish public schools, he entered Robert College American Engineering School in Istanbul, Turkey. In 1958 he received his Bachelor of Science Degree in Civil Engineering. He came to the United States and enrolled at the Missouri School of Mines and Metallurgy in February, 1960 for graduate studies.